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Micro-Scale Hydropower for the Eighties

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MICRO-SCALE HYDROPOWER FOR THE EIGHTIES

BY

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RESEARCH REPORT

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ABSTRACT

The objectives of this project are to show the feasibility of micro-hydropower and to provide adequate engineering data for those people who wish to design their own micro system.

Nine case studies are reviewed and analyzed in an attempt to determine general design parameters. Comparative data for these studies comes from preliminary permit applications submitted to the Federal Energy Regulatory Commission.

Information on such topics as flow measurements, heads, generators and turbine technology are presented. Duration curves are explained with examples using data from a river found in Colombia, South America.

Finally, a preliminary design of a micro-hydro facility is calculated for implementation on a stream that is part of the Tennessee River Basin.

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CHAPTER I

INTRODUCTION

Hydropower is one energy source that has been trapped for centuries and will continue to be so because its fuel is simply water and thus inexhaustible.

Hydropower uses the potential power of water carried by a river. It is created when there is a vertical distance (or head) between the point where the water is taken from the river and the point where it finally passes through a turbine. Sometimes this occurs naturally and other times it is necessary to construct high dams to obtain the required head to produce the desired amount of power.

Micro-hydropower uses these same principles, only on a smaller scale. Its production of electricity ranges between 2 and 50 KW's as opposed to large dams which can produce up to 12 million KW's.

Now becoming more popular, micro plants can help to develop the 470 billion kilowatt-hours per year that are estimated to be this country's underdeveloped water resources. Here, there are thousands of dams that have been abandoned. Where once they created power for mills, now they can be reactivated to produce electricity. According to surveys (shown later in this report), many of these dams can produce more than 60 KW.

Micro-hydroelectric production should be seriously considered by those countries where mountains and streams are plentiful.

Developing countries like Colombia, Ecuador and India could help to free themselves from dependence on foreign energy by investing more in their own natural water resources. This type of power can be particularly beneficial in rural areas that are beyond the reach of electrical power lines. Up until now, most of these regions have relied on diesel plants, but these kinds of facilities are becoming increasingly more expensive to operate.

In China, more than 85,000 small hydroelectric plants have been installed with a production of approximately 60 KW's each. This totals more than 5 million KW's of power.

Individual landowners can make power not only for themselves but can also (with an equal capital investment and small design variations) generate additional power to sell to the local municipal electric company or to anyone else who lives nearby willing to buy it.

A micro-hydro plant's most expensive outlay is its initial capital investment. This, though, can be reduced by utilizing local labor and materials. Even the turbine which requires rather technical knowledge to design can be manufactured in a local cast iron factory.

Now that the public is becoming more concerned with environmental pollution, the traditional ways of producing power are being questioned. Problems such as nuclear waste which is untreatable cannot be ignored. Nuclear power plants are producing 10,000 gallons of radioactive waste each year which will last for approximately 250,000 years! In 1973, storage tanks of the Atomic Energy Commission (AEC) leaked 115,000 gallons of radioactive waste into the environment (Capp 1973). In 1979, the Three Mile Island accident cost millions of dollars to the government just in the evacuation of the area.

It is necessary to develop those resources that will not destroy our environment. Micro-hydropower is one of the best ways to produce energy and at the same time be in harmony with nature because water leaves the turbine as clean as it entered without any chemical or physical alterations.

CHAPTER II

HISTORY AND FUTURE OF MICRO-HYDROPOWER

Mankind has been harnessing the power of water for thousands of years. The first kind of waterwheel was probably the Norse or Greek horizontal-type. It could be found in the hills of the Near East around 50 BC. The horizontal wheel had small paddles and a vertical shaft passing through its center which was connected to the mill.

The Norse wheel produced up to a ½ horsepower. It could, however, work only with fast moving water and thus, was restricted to steep lands (Harper, S. 1980).

Hydropower was understood during the Roman Empire but was not frequently used because slavery provided most of the power that the society needed. In this time period, the use (or lack of use) of water power was shaped more by social and political conditions than by technical knowledge.

By the 11th Century, water power was being used to grind grain, produce olive oil, make wine, swing hammers and maintain blast furnaces (Gimpel 1976).

In the 14th Century, water mills became more widespread and by the middle ages, thousands were in operation throughout Europe (Wolfe 1960).

When the settlers came to North America, it appears that the first waterwheels used were for sawmills. One of the most abundant natural resources available to the pioneers were the forests. Sawmills permitted them to not only build homes and stores but also provided them with a valuable trading commodity.

In addition to sawmills, water power was also used for grinding grain, manufacturing ironworks, and preparing woven and other plant fibers for cloth. In Saugus, Massachusetts, an ironworks mill was operating in 1646. This particular mill has been renovated and is presently working today.

Most of the settlers used the types of mills prevalent in their native countries. Swedish settlers, for example, in Delaware used the Norse type of mill.

The horizontal mill was relatively cheap and simple to construct. It had no gearing and was made almost entirely of wood. At the bottom of the mill was a horizontal wheel. Water was carried in a wooden or stone trough and discharged against the wheel's blades.

As the wheel turned, it rotated a vertical shart that was connected to a mill stone above. Beneath the wheel, the vertical shaft fitted into a support unit which carried the weight of the shaft, the wheel and the mill stone. The support unit was often mounted on a beam which could be raised or lowered in order to change the distance between the grinding stones, making for finer or coarser meal (Hindle 1960).

Today, there are still operational horizontal mills in the world. They can be found in many mountainous areas of Latin America, Portugal and Spain.

A slight variation to the horizontal mill occurred when its waterwheel was enclosed. This enclosure was similar to a large bottomless tub or barrel. The sides of the tub prevented the water from escaping sideways and supposedly improved the efficiency of the wheel.

Even more efficient than the Norse and tub wheels were the vertical waterwheels (with horizontal drive-shafts). This type of wheel has four variations: (1) the overshot, (2) the pitchback, (3) the breastshot and (4) the undershot.

If the wheel is regarded as a clock and the water enters it from the left side, the overshot wheel would be fed between 12:00 and 1:00, the pitchback at about 11:15, the breastshot between 8-10:30 and the undershot at about 7:00.

Vertical waterwheels were built with five major parts: the shaft, the arms or spores, the rims, the drum boards and the partitions that formed the buckets. The shafts were usually made of oak, approximately 20" in diameter. The ends of the shafts were wrapped in iron and rested on support bearings made of wood, stone or brass.

Many waterwheel parts were built with pine or cypress. Cypress was found to be the best material for waterwheels because it was highly rot-resistant. Even with this type of timber, though, it was usally necessary to replace or repair most of the parts every 5-10 years.

For vertical waterwheels to turn horizontal mill stones, gearing was required. The drive shaft was fastened to a large gear which in turn meshed with a lantern pinion. The ratio of these two gears varied but was more or less 1:5. Some people used ratios like 1 to 5.1 (for example, 10 cogs on the lantern pinion and 51 on the face wheel). In doing this, the same two cogs would not continuously meet and cause uneven wear.

There have always been geographical limitations on the use of waterwheels. Areas like the Great Plains and the Midwest with relatively few streams and lots of flat land used much less water power than the rest of the United States. The twelfth census taken in this country in 1900 showed the number of waterwheels in use in the Midwest (see Table 1) (Hyde 1978; Twelfth Census of the U.S. 1900).

The Use of Hydropower in Producing Electricity

It was not until the 19th century that water power became a means for producing electricity. Around 1825, the French engineer, Fourneyron, invented the turbine. This device could move more than 10 times the speed of the average watersheel and could produce more than twice the power. For the first time in man's history, the generation of hydroelectricity had become feasible.

TABLE 1

WATERWHEELS IN THE MIDWEST IN 1900

Area	Number	Capacity in Horsepower	Horsepower per Waterwheel
Illinois	319	13,175	41
Indiana	492	15,510	31
Iowa	543	12,159	22
Kentucky	572	9,284	16
Michigan	998	42,888	42
Minnesota	339	26,953	79
North Dakota	20	581	29
Ohio	867	24,219	27
South Dakota	50	1,466	29
Wisconsin	1,589	99,007	62
Midwest Total	5,789	245,242	42
United States	39,182	1,727,258	44

As time passed, more uses were found for electricity. Thomas Edison developed incandescent lamps and in order to supply them with power in Appleton, Wisconsn, he founded a small hydroelectric plant on the Fox River in 1882.

In 1895, a breakthrough in the long distance transmission of electricity occurred at Niagara Falls. A hydroelectric power plant created electricity that was carried more than 20 miles away to Buffalo, New York (World Book Encylopedia).

The use of hydroelectricity has increased significantly since 1895. During the 20th century, huge dams have been constructed for the purpose of supplying electricity to large communities and exploiting mineral resources by means such as aluminum smelting.

During the 1960's one of the largest hydro facilities in the world was built in Egypt. Known as the Aswan High Dam, it weighs almost 20 times more than the pyramid of Cheops and supplies enough electricity for 99% of the country's villages (Mermel 1979).

Soon to be completed, the Itiapu of Brazil will generate up to 12,000 megawatts. But this may only be the beginning for this South American nation because it is now considering using the Amazon River to flood an area the size of Montana and having a hydroelectric facility capable of producing 66,000 megawatts (Deudney 1981).

In the beginning, these magnificent hydro facilities were simply considered a credit to the field of Civil Engineering, particularly in that they did not pollute the environment. As time passed, though, people started to become more concerned about the tremendous ecological changes that occur when these massive projects are undertaken. Frequently, wildlife, plants, and trees are flooded and people's homes are displaced.

In Australia, for example, a hydroelectric complex was built in Lake Peddler National Park. Ecologists and environmentalists protested against the construction of this project because many species found only in the island state of Tasmania would be killed off by the necessary flooding (Scott 1979).

In the United States, the Tellico Dam was erected in the Tennessee Valley. Even after years of construction, it is still provoking critics because of the displacement of homes and the reduction of an endangered species known as the snail darter (A.B.C. Evening News, November 1981).

If the Brazilians decide to flood the Amazon River, the already shrinking indian tribes will undoubtedly be moved away from their habitats and lifestyles that have existed for centuries. Much of the famous Amazonian vegetation and wildlife will be destroyed (Deudney 1981).

With the increase of the environmental protests over the past decade, governments have been investigating alternatives to massive dams and recently the old abandoned small hydro facilities have risen in popularity in both developed and developing nations.

There is presently a study that is evaluating the theoretical potential of existing dams and small "low head" hydropower facilities in the Pacific Northwest Region of the United States. The area in question includes the Columbia River and river basins of Idaho, Oregon and Washington. The total area is about 292,000 sq. miles. The heads are between 3 and 20 meters and the flows are at the 50% exceedance level on the duration curve (Gladwell 1980).

While the United States has so far generally remained in the research stage of this field, China has been vigorously tapping small hydropower. Since 1968, China has built approximately 90,000 small-scale hydro facilities. The average output of these units is 60 kilowatts and they contribute about 40% of China's total hydropower.

In Europe, the French have been leading the way in the development of small hydro technology. Presently, they have more than 1000 small hydrostations that generate more than 390 megawatts.

The French and the Chinese have demonstrated how communities can benefit from small dams. Electrifying rural areas can help to improve education, reduce unemployment, increase food production, and prevent urban sprawl.

With the successes of small hydropower, researchers have also been experimenting with what is known as micro-hydropower. This new area of study simply revives the old concept when water power drove single mills; only today it is driving modern generators in order to supply electrical needs for single dwellings.

The Future of Hydropower

In 1980, it was estimated that hydropower provided approximately 23% of our world's electric power. The degree to which hydropower is used is determined by the terrain and natural resources within each country. The oil rich nations of the Middle East, for example, use very little water power, while a nation such as Norway receives 99% of its electricity and 50% of its total energy from water.

On the North American continent, hydropower could produce 356,400 megawatts of electricity. At present, only 128,000 are being generated, as shown in Table 2. This information is supplied by the International Commission on Energy Conservation Research which was created in 1974 by 80 nations in order to determine all of the earth's energy resources, particularly those that could replace the diminishing supply of oil.

TABLE 2

HYDROPOWER POTENTIAL AND USE

Region	Technically Exploitable Potential (megawatts)	Exploited Resources
Asia	610,100	53,079
South America	431,900	34,049
Africa	358,300	17,184
North America	356,400	128,872
USSR	250,000	30,250
Europe	163,000	96,007
Oceania	45,000	6,795
World	2,200,000	363,000

Most of the world's hydropower potential is untapped as shown in Figure 1. It is calculated that only 17% of that which is available has been developed. The total thought to be developable amounts to 2.2 megawatts. This would produce roughly 10 million gigawatt-hours of electricity per year which is the same that is derived from 40 million barrels of oil per day.

All of these figures are estimated in relation to today's technology which is capable of tapping only 12% of all the theoretical energy from the world's rivers, oceans and streams.

The degree to which micro-hydropower will contribute to the world's future hydroelectric output will depend largely upon the development of the appropriate technology in this field. The more that micro technology can be improved, the more prices should decrease. This, in turn, will permit those people with access to rivers and streams an economical means to produce their own supply of power.

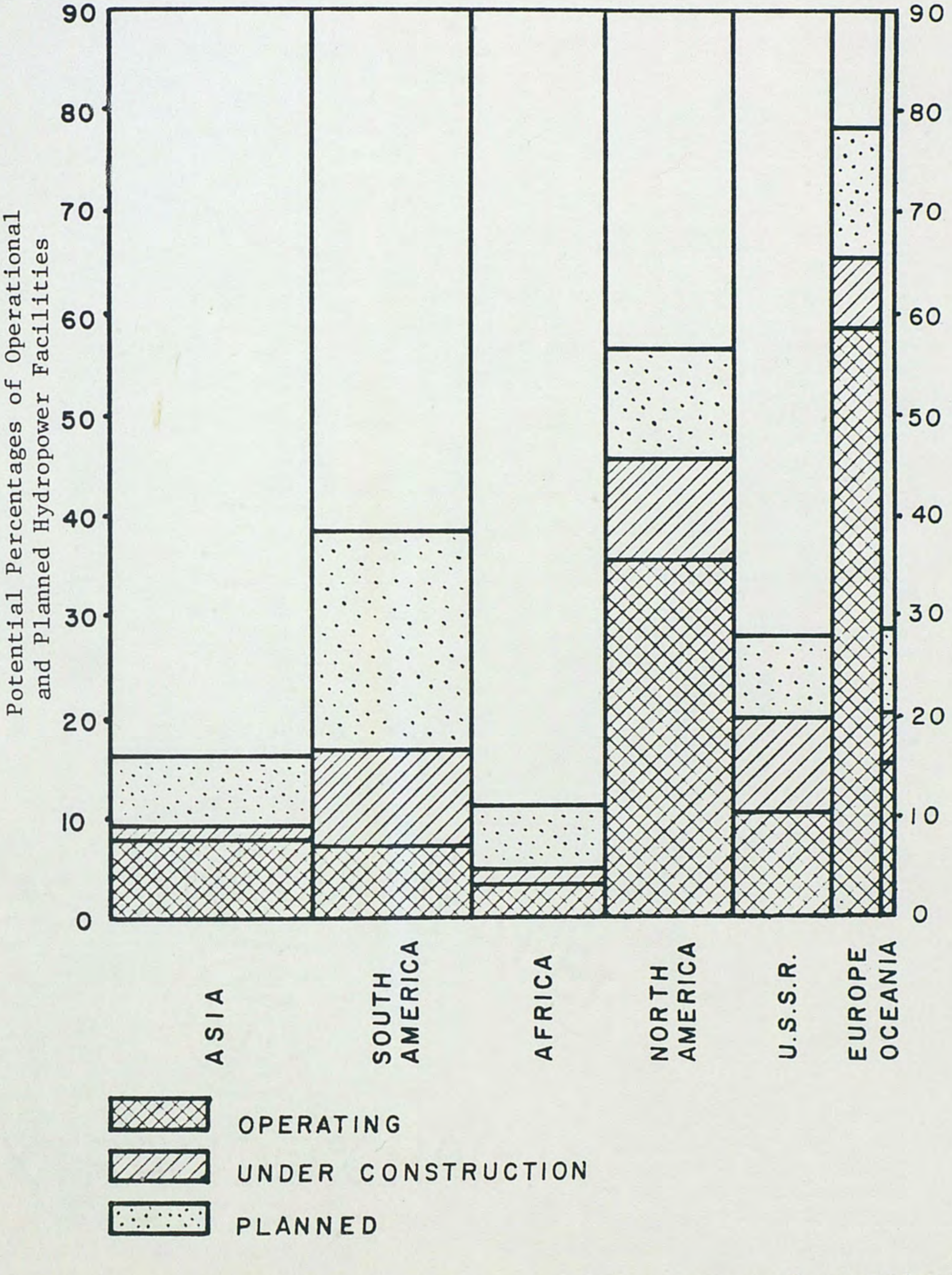


Fig. 1. The world-wide potential percentages of operational and planned hydropower facilities.

CHAPTER III

INFORMATION REQUIRED TO DESIGN A MICRO-HYDROPOWER PLANT

Physical Principles

Energy is the capacity to do work. Although energy can neither be created nor destroyed, one form of energy can be converted into another. The potential energy stored in water is converted into electricity in a hydroelectric plant by the following process:

Potential Energy → Kinetic Energy →
(water level) (motion of water)

Mechanical Energy → Electric Energy
(water wheel or hydraulic turbine) (electric generator)

The basic principles of hydropower can be expressed by saying that work is done when a force moves in the direction of its line of action and that power is generated when work is done over a period of time (Sterland 1965), as follows:

$$\text{Power} = \frac{\text{work}}{\text{time}} = \frac{\text{force x distance}}{\text{time}}$$

The following table (Table 3) shows the different ways that the above relationship can be expressed in hydropower calculations using the English and Metric systems.

TABLE 3

POWER CALCULATION FORMULAS

English Units*		Metric Units*	
$P = 62.4\ Q \times h \times e$	P = ft-lb/minute Q = cfm h = feet e = efficiency		
$P_{hp} = \frac{Q \times h \times e}{529}$	P_{hp} = horsepower Q = cfm h = feet	$P_{kw} = 9.81\ Qh \times e$	P_{kw} = kilowatts Q = CMS h = M
$P_{kw} = \frac{Q \times h \times e}{908}$	P_{kw} = kilowatts Q = cfm h = feet	$P_{kw} = \frac{Qh \times e}{102}$	P_{kw} = kilowatts Q = LPS h = m
$P_{kw} = \frac{Q \times h \times e}{11.8}$	P_{kw} = kilowatts Q = cfs h = feet		

* where: P = power
Q = flow of the stream
h = vertical net head
e = efficiency

Graph 1 shows the relationship between flow in gpm, head in feet and output energy in kwh/month, assuming a system efficiency of 53%.

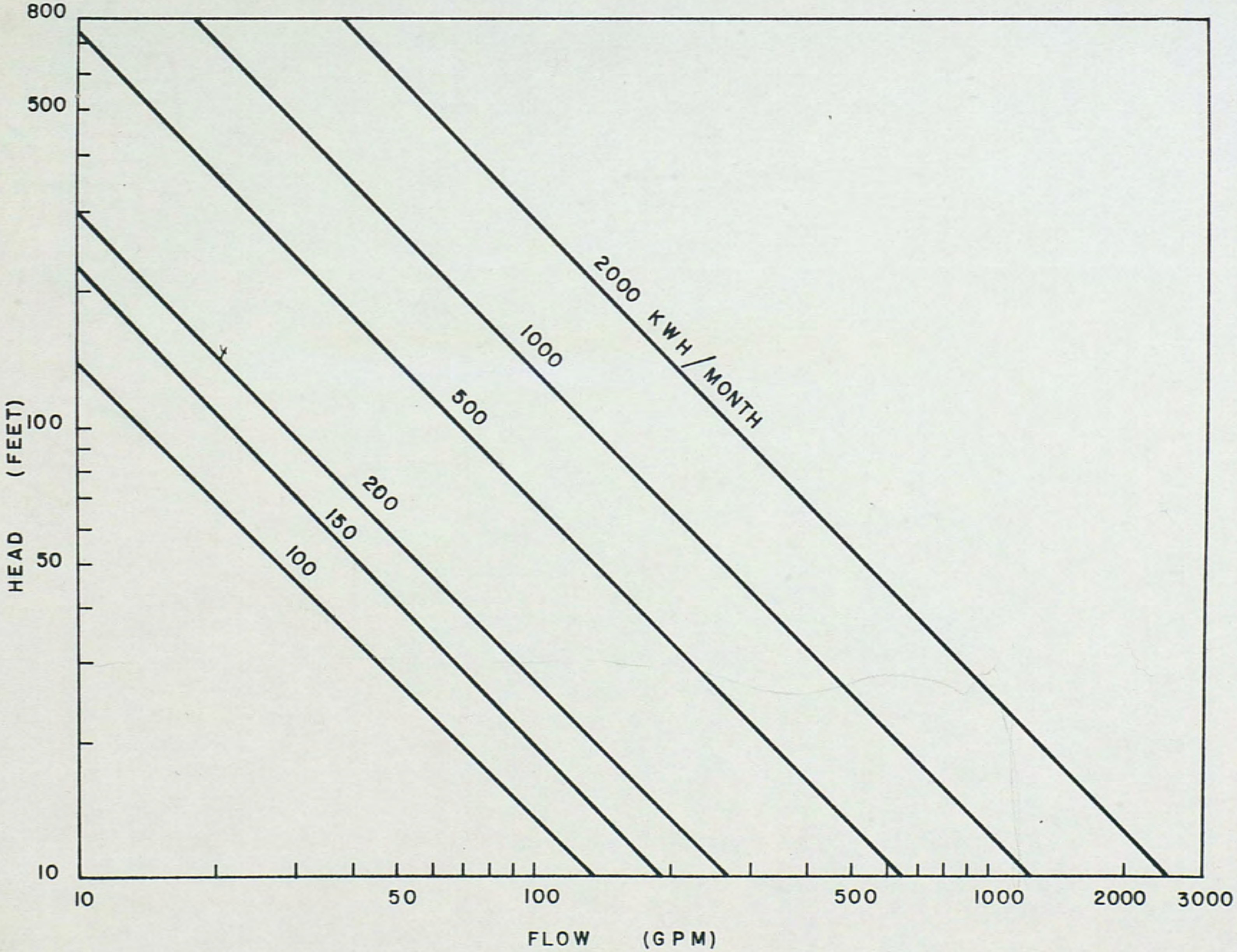
From this determination of power, in its application to hydropower, it is clear that the major variables affecting the quantity of power obtainable from the plant are the flow of the stream and the net available head of the terrain.

The real amount of electricity generated and the success of the investment depends upon the accurate gathering of this information. The proper methods for accomplishing this will be described in the following sections.

Flow Measurement

Micro facilities can be defined as "run-of-river" plants because unlike large hydro systems, they do not have storage reservoirs which can help regulate the flow of water during the year. Because of this limitation, it is very important to learn how to accurately measure and record the flow variations of the stream during the wet and dry seasons. Oftentimes, the ratio of flood water to low water exceeds one hundred to one.

Hydrologic analysis consists of different types of data: the river discharge, the precipitation, the type of drainage area, etc. River (or stream) discharge studies actually supply enough information to design a microhydro power unit, but for those who would like to consider precipitation, the World Meteorological



Graph 1. Energy generation at different flows and heads relationship.

Organization has published the "Guide to Hydro Meteorological Practices" which gives good guidelines for this kind of information (Gladwell 1980).

When designing a micro-hydro facility, it is necessary to know the flow available in the stream to be used. Local government agencies have publications on many rivers. In the United States, records are collected by the Geological Survey and published in their "Water Supply Papers". These papers report the daily river discharge of the 15 major American river basins and waterways according to their geographical location. The papers also include present and future utilization of the rivers (Grover 1966).

The different districts of the U.S. Weather Bureau publish records of precipitation and temperature in their "Monthly Weather Reviews". These reviews can be useful because river flows are affected by precipitation and frequently by temperature. Other government agencies that may be of use to a micro-hydro designer are the U.S. Army Corps of Engineers, the Public Health Service, the Soil Conservation Service, and the Bureau of Agricultural Engineering. In addition to these, information can sometimes be obtained from state governments (Nathan 1966).

Methods of Measurement

In general, people who wish to design a micro-hydro system must gather their own information because government agencies usually supply data only on large rivers. This means that the designer should start by learning how to measure, record and interpret the flow variations of the stream.

There are several methods of measuring the velocity of a river's current. The following systems were studied at a microhydropower workshop in July, 1981 at the Appalachian State University in Boone, North Carolina.

The Meter Flow

This method consists of recording the number of revolutions made in a given time by a propeller placed at different depths. The turns of the propeller are recorded by an electrical break-circuit (Hammond 1958).

The meter is calibrated by being passed at a known velocity through still water. This is one of the best and most popular methods used in measuring the flow of a large stream.

The "small price meter" can be operated by extending a cable across the stream. The meter can be carried by a pulley to any desired point and then lowered to any part of the river channel. Insulated wires connect the propeller axle to the recording unit on shore.

If the stream that is being measured is navigable, then it is impractical to use a cable. In this case, the meter must be lowwered from a boat anchored in the water.

For small streams, the pygmy current meter is recommended because it can operate reliably near the surface of the water and in shallow depths. It can also measure very low velocities. At Boone, records were taken using a pygmymeter counting the amount of turns the propeller made in 30 seconds. This time can vary up to 10 minutes according to the velocity of the flow (see Figure 2).

There are many kinds of flow meters available on the open market. The meter shown in Figure 3 is calibrated in cm/s. It does not have an electrical counting system. The number of turns are recorded mechanically by the meter. Its cost is $150.

The velocities in a channel are not evenly distributed because of friction along the channel walls and free surface. The velocity distribution also depends on the shape of the waterway, its roughness and the presence of bends (Chow 1959).

The U.S. Geological Survey recommends the following method for gaging a stream. Divide the cross-section into vertical strips by a number of successive verticals. The velocity is measured at 0.6 of the depth of each vertical (if the stream is not too deep). In the other case, the velocities should be the average at 0.2 and 0.8 of the water's depth.

The average of the mean velocities in any two adjacent verticals multiplied by the area between the verticals gives the partial flow for each section. The sum of all the partial flows will be the total flow of the stream in this particular section. (See Figure 4).

Fig. 2. A pygmymeter ($900.00).

Fig. 3. A mechanical flow meter ($150.00).

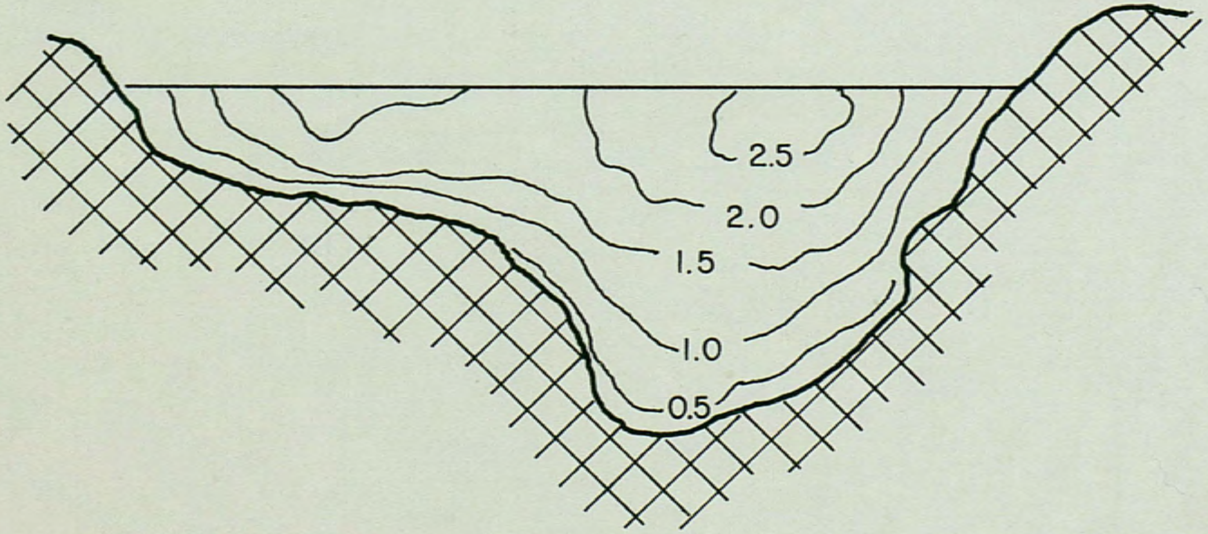


Fig. 4. Typical curves of equal velocity in a natural irregular channel.

Figures 5 and 6 show how the flow meter should be placed using the tape measure's divisions.

Fig. 5. Placing of flow meter.

Fig. 6. Placing of flow meter.

The Weir Method

For narrow streams, the weir method is the most advisable. The weir is built like a dam across the stream and forces the water to pass through a rectangular notch with a known dimension. This notch should have a width to height ratio of at least 3:1. The height of the surface of water running over the weir is measured which can be done very accurately by means of a hook gauge or similar apparatus (see Figure 7 and Table 4)(Alward 1979).

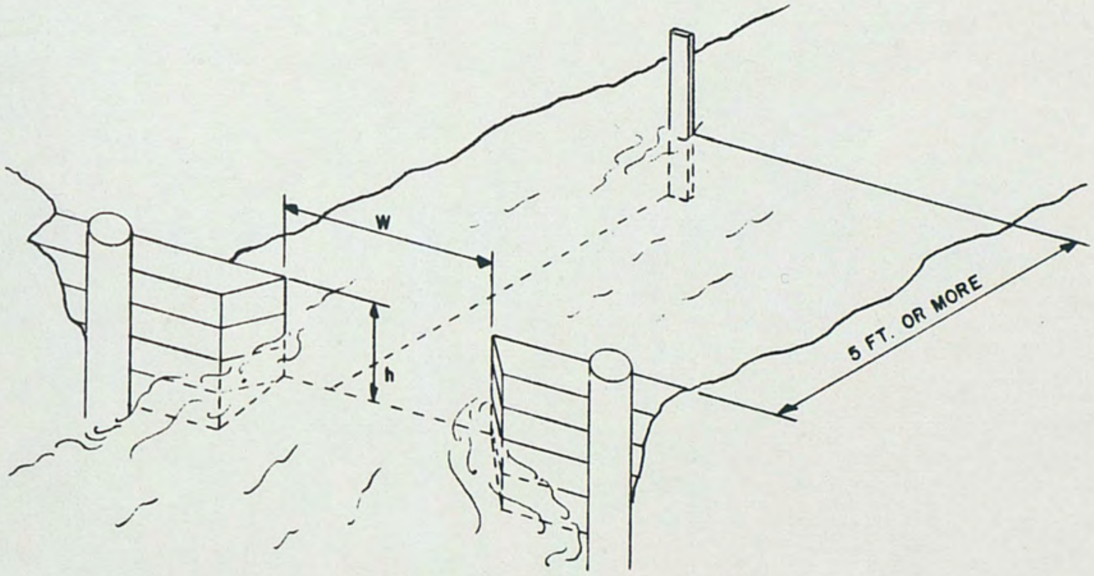


Fig. 7. The Weir Method.

TABLE 4

WEIR TABLE

Depth on Stake in inches	c.f.m.per inch of notch width
1	0.40
1.25	0.55
1.5	0.74
1.75	0.93
2	1.14
2.25	1.36
2.5	1.59
2.75	1.83
3	2.09
3.25	2.36
3.5	2.63
3.75	2.92
4	3.22
4.25	3.52
4.5	3.83
4.75	4.16
5	4.50
5.25	4.84
5.5	5.18
5.75	5.54
6	5.90
6.25	6.28
6.5	6.65
6.75	7.05
7	7.44
7.25	7.84
7.5	8.25
7.75	8.66
8	9.10
8.25	9.52
8.5	9.96
8.75	10.40
9	10.86
9.25	11.31
9.5	11.77
9.75	12.23
10	12.71
10.25	13.19
10.5	13.67
10.75	14.16
11	14.67
11.25	15.18
11.5	15.67
11.75	16.20
12	16.73
12.25	17.26
12.5	17.78
12.75	18.32
13	18.87
13.25	19.42
13.5	19.97
13.75	20.52
14	21.09
14.25	21.65
14.5	22.22
14.75	22.70
15	23.38
15.25	23.97
15.5	24.56
15.75	25.16
16	25.76
16.25	26.36
16.5	26.97
16.75	27.58
17	28.20
17.25	28.82
17.5	29.45
17.75	30.08
18	30.70
18.25	31.34
18.5	31.98
18.75	32.63
19	33.29
19.25	33.94
19.5	34.60
19.75	35.27
20	35.94
20.25	36.60
20.5	37.28
20.75	37.96
21	38.65
21.25	39.34
21.5	40.04
21.75	40.73
22	41.43
22.25	42.13
22.5	42.84
22.75	43.56
23	44.28
23.25	45.00
23.5	45.71
23.75	46.43
24	47.18

The Float Method

This method consists of observing the velocity of water with the aid of an object floating down the stream. This is done from two shore stations, the distance between which is known. Such a float may consist of a barrel or tin vessel attached to a rod and loaded so that a short length of the rod projects above the water surface. The flow is found by multiplying the cross-sectional area of the stream by its velocity. This method is only used to get a rough idea of the discharge of the river.

Flow Duration Analysis

At the selected site, a hydrologic analysis of the stream can be performed by recording the flow during a predetermined time series. A time series study consists of a sequence of values gathered for a particular variable over a specified period of time.

Most hydrologic time series are categorized as being discrete. This means that observations are made at specific time intervals (represented as ΔT). If, for example, observations are recorded once a day, $\Delta T = 1$ day, or if observations are taken and averaged weekly, $\Delta T = 1$ week.

Some hydrologic time series studies are categorized as being continuous. This sometimes occurs at stream gaging locations where there is a system that continuously records the stream's flow rate. Even here, though, analysis is usually computed by plotting values taken every so often (Han 1977).

The information must be recorded in such a way that flow duration curves can be plotted. This may be accomplished by taking the average flow rates per day, week, month or year. These rates are then ranked in order. The largest value being #1, the next value #2 and so on.

The number of times that each rate occurs is divided by the total amount of samples taken. This figure is then multiplied by 100 to represent the percentage of time intervals (year, month, etc.) that a particular flow rate has occurred or been exceeded.

Now, a working curve can be drawn, plotting the flow values against their percentage of occurrences. Once accumulated, this information is used to predict the potential power that can be developed.

The frequency of time chosen for collecting data depends upon how the data will be used. Most micro-hydropower facilities, for example, can be adequately designed with information gathered daily or weekly. As with most statistical analysis, the value of the information is a function of the size of the total record (Gladwell 1980).

Flow duration curves are usually drawn with figures like Q_{50} or Q_{30}, where Q represents a particular flow rate and the numeric subscript represents the percentage that the flow rate has occurred.

To estimate a micro system's potential, one can use a model comprised of the daily flow rates taken over a selected number of years. In this model, 365N days would represent 365 days for N number of years. When using this method, it is beneficial to compare the annual hydrographs so that the critical periods of excessive wetness or dryness can be recognized.

This same system of analysis can be done by taking monthly mean values. In this case, the record will consist of 12N items. The problem with this particular method, though, is that monthly mean values will not show variations within the month and the resulting flow duration curve will look different from that which is derived from a daily flow analysis. This same disadvantage occurs when annual mean values are used to create flow duration curves (Gladwell 1980).

The duration curve shows the percentage of time during which the stream's discharge and consequently the plant's output of energy is above or below any particular rate.

The power derived from the different flow rates will be determined by the size and number of turbines that will be used. This is so because micro facilities do not store water.

If it is not necessary to generate all the electrical potential from the river, it is definitely more economical to use a single non-adjustable turbine. In this case, it is advisable to select Q_{80} or Q_{90} from the duration curve when choosing the size of the equipment.

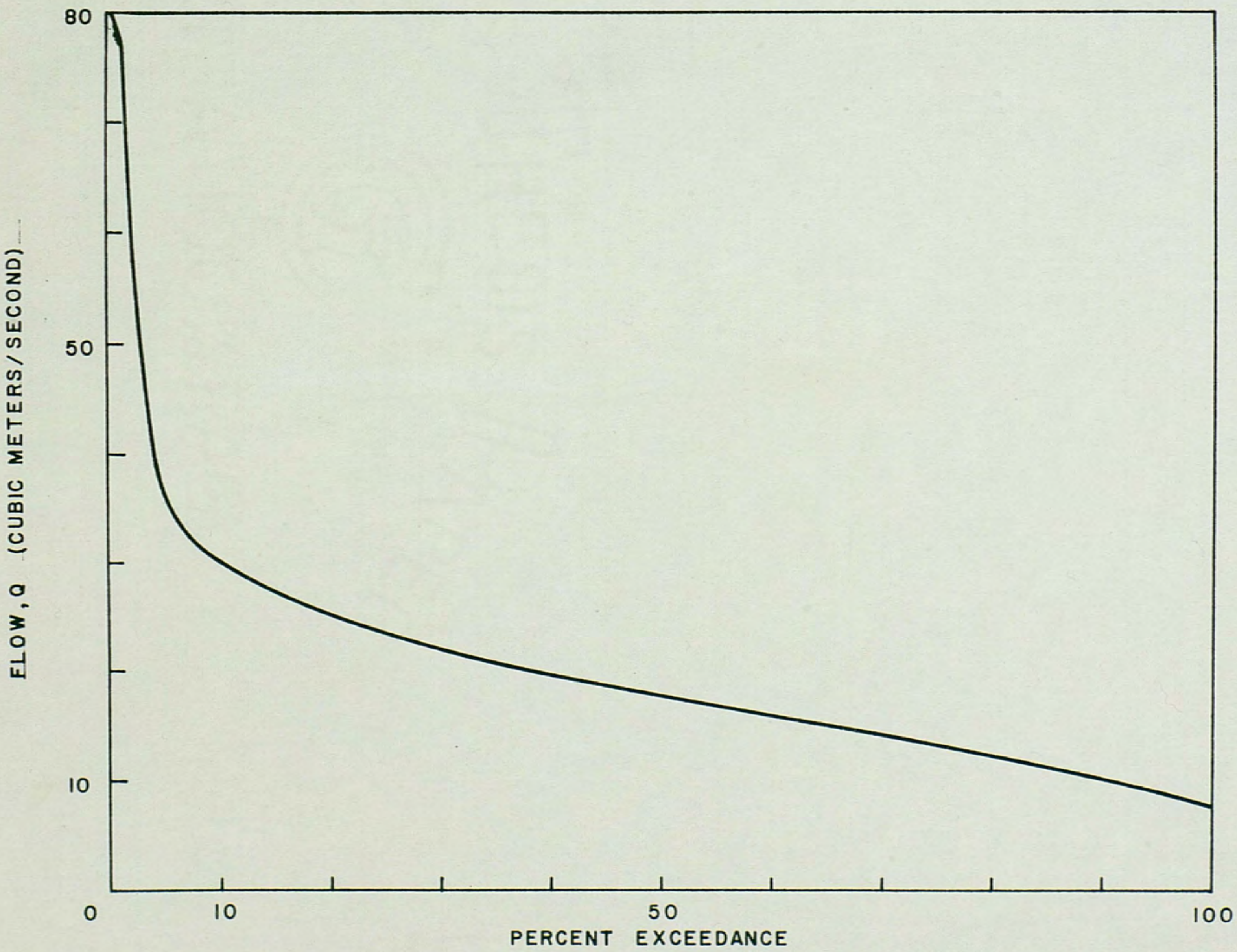
To compliment the information provided by the duration curve, it is helpful to plot a hydrograph. This type of graph shows the river's discharge on the vertical axis and the time that each flow occurs on the horizontal axis. A discharge hydrograph simply shows the increments of flow in the time sequence in which they occur while a duration curve shows the percentage of times they occur.

An example of a flow duration curve can be seen in Graph 2, while a hydrograph is plotted in Graph 3. The data for these curves was obtained from the Ovejas River in Colombia, South America. The organization responsible for this hydrologic information was the "Corporacion Autonoma Regional del Cauca" (C.V.C.). This government agency reports on many of the rivers in the midwestern part of the country. The flow of the Ovejas River was calculated by using the Manning and Stevens calibration curves (Corporation Autonoma del Valle)(See Tables 5 and 6).

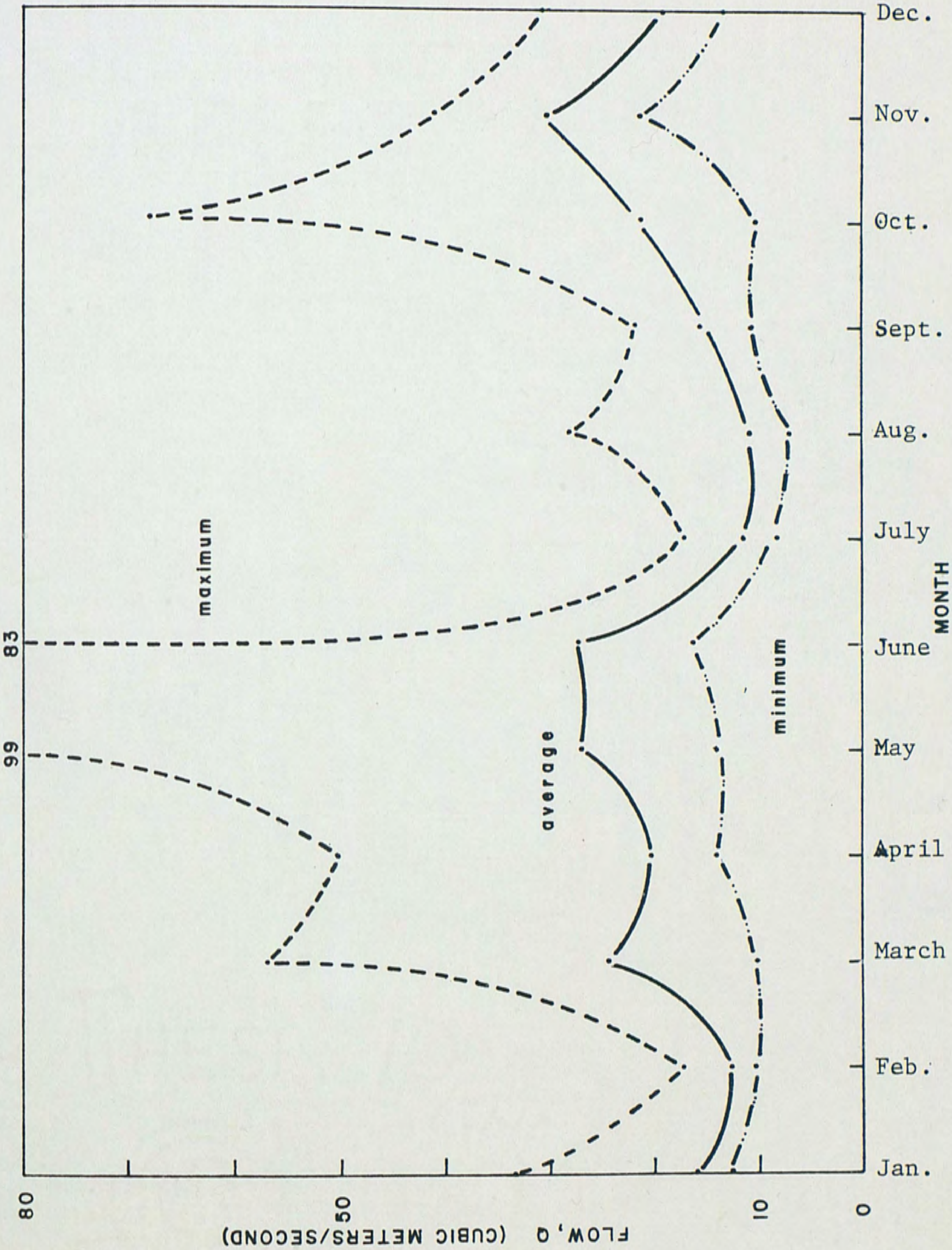
In the United States, the Idaho Water Resources Research Institute has been performing a survey to determine the theoretical power and energy of certain Pacific Northwestern rivers and streams. The duration curves used for this project were determined for different gaged and ungaged points along the streams. The curves of the ungaged points were estimated using three different methods.

The first is known as the Idaho Method. This interpolation-extrapolation system uses ratios of stream length and drainage area to adjust historical flows from a gaged to an ungaged point.

The second, or Washington Method, uses basin characteristics,



Graph 2. Flow-duration curve for Rio Ovejas, Colombia, year = 1979.



Graph 3. Hydrographs for Rio Ovejas, year = 1979.

TABLE 5

CVC

CORPORACION AUTONOMA REGIONAL DEL CAUCA
DEPARTAMENTO DE AGUAS — SECCION DE HIDROCLIMATOLOGIA

CAUDALES PROMEDIOS DIARIOS EN m^3/s

RIO OVEJAS ESTACION ABAJO AÑO 1979

LONGITUD: 76°36'
LATITUD: 2°52'
ELEVACION: 1260 M.S.M.
AREA DE DRENAJE: 607 Km2
MUNICIPIO: BUENOS AIRES
DEPARTAMENTO: CAUCA
INSTRUMENTO: LIMNIGRAFO
TABLA DE CALIBRACION:

DIA	ENE.	FEB.	MAR.	ABR.	MAY.	JUN.	JUL.	AGO.	SEP.	OCT.	NOV.	DIC.
1	15.7	13.8	11.1	21.5	38.7	79.8	16.5	9.0	22.0	10.8	26.0	26.0
2	14.5	14.5	11.5	20.8	29.7	78.7	13.8	7.8	20.8	10.8	26.5	27.0
3	14.2	12.8	10.5	21.1	29.7	73.9	14.9	9.3	12.5	10.8	25.0	28.1
4	13.8	12.5	12.8	18.8	26.5	53.6	14.5	8.7	13.5	10.8	24.5	26.0
5	15.7	13.8	19.6	18.4	21.9	27.5	12.8	9.3	12.5	10.8	22.0	26.0
6	14.5	12.1	25.0	17.6	24.0	23.5	12.1	9.3	12.8	10.8	27.5	26.0
7	14.2	12.8	24.5	20.4	22.9	20.0	10.8	9.3	14.9	10.8	31.3	24.0
8	16.8	12.8	29.2	16.5	20.8	21.5	10.8	7.8	14.5	10.2	31.9	24.5
9	17.6	12.1	24.0	17.6	21.1	20.8	10.8	7.8	14.9	10.5	31.9	21.5
10	16.5	11.5	22.9	17.2	20.4	22.4	10.5	7.8	15.3	12.1	31.3	20.8
11	18.8	11.5	19.2	16.8	21.5	24.5	10.2	7.8	16.1	12.1	30.3	20.4
12	16.8	12.5	18.8	14.9	21.1	23.5	10.5	7.6	16.8	10.8	29.7	20.0
13	14.2	11.5	21.5	14.5	18.0	22.4	11.5	7.3	18.4	14.2	29.7	19.6
14	14.5	12.1	20.8	14.2	16.5	22.0	12.1	7.3	20.8	15.3	34.1	18.0
15	28.6	11.8	20.4	14.2	16.5	21.5	10.8	7.3	22.0	12.1	38.7	14.2
16	28.1	14.2	20.0	14.5	19.6	23.5	13.1	7.3	14.5	35.2	41.1	14.9
17	15.3	14.2	24.0	14.2	19.6	21.5	12.1	7.3	15.3	65.0	39.9	15.3
18	14.2	11.1	20.0	14.5	20.0	20.8	12.1	7.6	15.7	29.2	31.9	15.7
19	14.5	13.8	29.2	16.8	21.1	20.8	10.8	7.8	16.1	27.0	29.2	16.1
20	14.9	15.3	31.9	18.0	21.9	20.4	10.8	7.8	15.7	39.9	29.7	16.5
21	14.2	12.1	29.7	18.0	21.5	19.6	10.8	9.9	16.1	32.4	33.0	16.8
22	13.5	11.8	30.2	18.8	21.1	19.2	10.8	8.4	15.7	22.0	35.2	16.5
23	17.6	11.5	27.0	20.4	21.5	18.0	10.2	9.0	15.3	18.0	31.9	16.8
24	15.3	13.5	30.2	22.4	21.1	17.6	10.2	12.1	15.7	26.5	30.2	18.0
25	16.1	13.8	39.9	22.9	22.4	17.2	10.2	14.2	14.5	32.4	29.2	18.2
26	14.2	12.8	50.3	23.5	21.9	16.8	10.2	14.5	14.2	33.5	28.6	17.0
27	13.8	12.5	37.0	25.5	25.0	16.8	9.9	15.7	13.8	27.0	29.2	16.3
28	18.4	12.1	26.5	31.3	25.0	18.0	9.3	16.1	14.5	25.0	28.1	15.1
29	15.3		26.5	47.2	58.9	17.2	9.6	20.4	13.8	24.5	27.5	14.5
30	15.3		24.0	41.1	72.0	16.8	9.6	28.1	14.5	24.0	26.5	13.4
31	15.7		22.4		76.7		9.6	27.5		26.0		14.8
TOT.	502.8	356.8	760.6	613.6	838.6	819.8	351.9	337.1	473.2	660.5	912.1	598.0
PROM.	16.2	12.7	24.5	20.5	27.1	27.3	11.4	10.9	15.8	21.3	30.4	19.3
MAX.	33.5	17.2	56.9	50.3	99.1	83.0	17.2	28.1	22.0	68.3	41.1	30.7
MIN.	12.8	10.5	10.2	14.2	14.2	16.5	8.4	7.3	10.8	10.2	21.5	13.4

CAUDAL PROMEDIO ANUAL: 19.7 MAX. OBS. 99.1 MIN. OBS. 7.3

TABLE 6

INFORMATION REQUIRED TO PLOT THE DURATION CURVE FOR OVEJAS RIVER

Flow	Cumulative % Time	Flow	Cumulative % Time
79.8	0.274	30.8	9.316
78.7	0.548	30.2	10.138
76.7	0.822	30.0	
73.9	1.096	29.7	11.782
72.0	1.370	29.2	13.426
65.0	1.644	28.6	13.974
58.9	1.918	28.1	15.07
53.6	2.192	27.5	16.166
50.3	2.466	27.0	17.252
47.2	2.74	26.5	18.906
41.1	3.288	26.0	20.55
39.9	4.11	25.5	20.824
38.7	4.658	25.0	22.194
37.0	4.932	24.5	23.564
35.2	5.48	24.0	25.208
34.1	5.754	23.5	26.304
33.5	6.028	22.9	27.126
33.0	6.302	22.4	28.496
32.4	6.85	22.0	29.866
31.9	8.22	21.9	30.688
31.3	9.042	21.5	33.154
20.8	37.264	21.1	34.798
20.4	39.182	13.4	75.35
20.0	40.552	13.1	75.624
19.6	41.922	12.8	77.542
19.2	42.47	12.5	78.912
18.8	43.566	12.1	82.474
18.4	44.388	11.8	83.022
18.2	44.662	11.5	84.666
18.0	46.854	11.1	85.214
17.6	48.224	10.8	89.598
17.2	49.046	10.5	90.694
17.0	49.32	10.2	92.338
16.8	52.06	9.9	92.886
16.5	53.978	9.6	93.708
16.3	54.252	9.3	95.078
16.1	55.896	9.0	95.626

TABLE 6 (Continued)

Flow	Cumulative % Time	Flow	Cumulative % Time
15.7	58.362	8.7	95.9
15.3	61.102	8.4	96.174
15.1	61.376	7.8	98.092
14.9	63.02	7.6	98.64
14.8	63.294	7.3	100.01
14.5	67.678		
14.2	71.788		
13.8	74.254		
13.5	75.076		

weather data and past date streamflow information as input parameters for regression equations.

The third, or Montana Method, uses historical gage records to develop parameters such as standard deviation and serial correlation coefficients in order to generate synthetic streamflows (Emmert 1979).

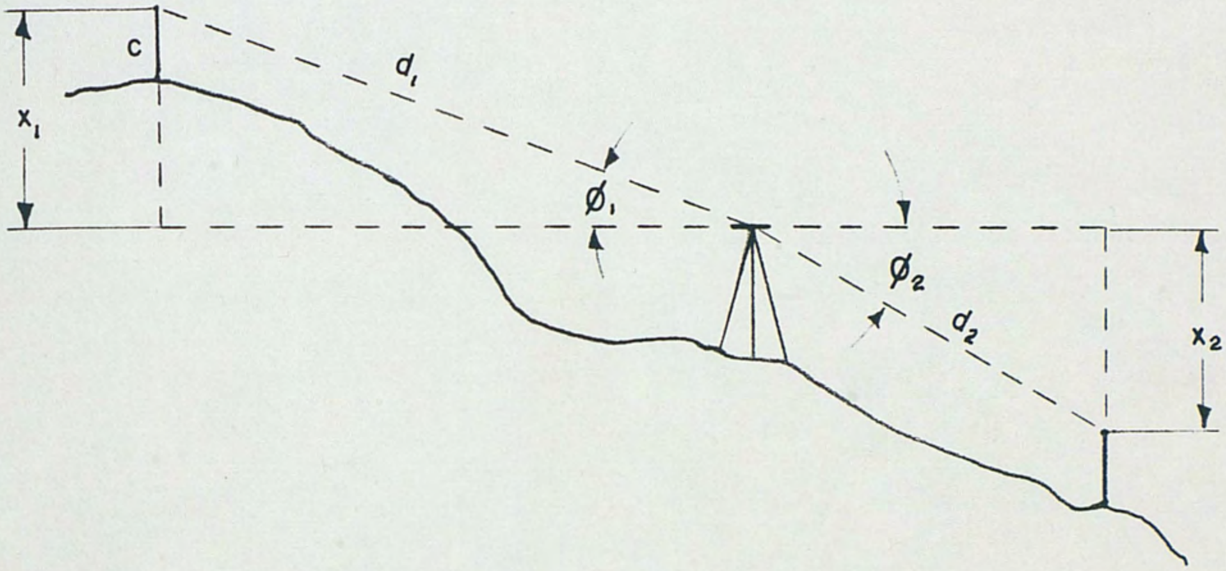
Another method employed to obtain flow duration curves relates flow rates to certain meteorological variables. In New England, for example, precipitation varies from 20" to 30" each year. Duration curves have been formulated where $Q_{20} - Q_{30}$ percent exceedence flows correspond to 2 cfs for each square mile of drainage area.

Total Head Measurements

The gross head available on a hydroelectric system is determined by calculating the difference in elevation between the point where the water enters the conduit and the point where the water passes through the turbine. This distance, though, may vary because both levels do not always remain constant.

The gross head can be obtained from topographical maps of the area or by measuring with surveying equipment or using a hand level.

Figure 8 shows the angle method which is used to measure the vertical head with a transit.



d = Distance (measured)

ϕ = Angle (measured)

c = Constant Rod

$x_1 = d_1 \times \sin \phi_1$

Total Head = $x_1 + x_2 + x_3 + \ldots x_n$

Fig. 8. The Angle Method.

Figure 9 shows how to measure with a hand level, used at Laurel Creek, Watauga County, North Carolina.

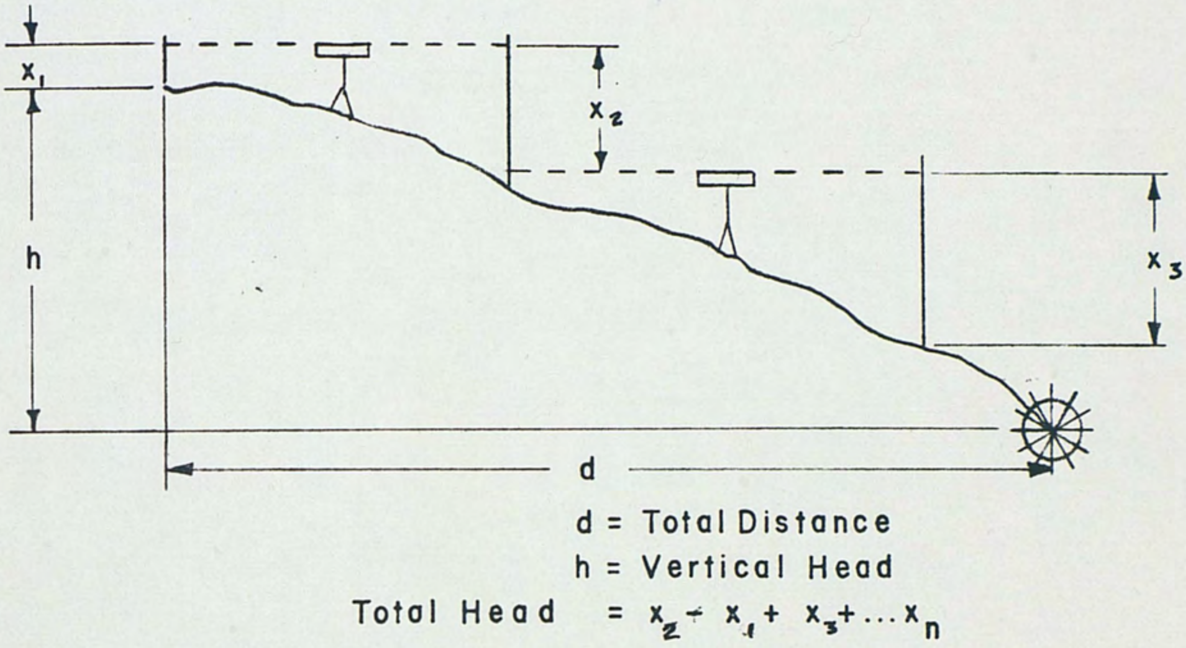


Fig. 9. Measuring using a hand level.

Net Head Calculation

The net or effective head is the head determined by deducting all losses produced while the water passes between the intake point or head race and the turbine intake point. These losses occur primarily because of friction in the penstock (the total system that carries the water to the turbine).

For turbine installations that are operating with low heads (5-10 feet), it is also important to consider the level of the water after it passes through the turbine. This tail water can reach 1 foot in height and, in so doing, reduce the already low net head. This would, in turn, lower the overall efficiency of the hydro facility.

The head loss owing to friction losses can be calculated from nomographs or flow charts. If these are unavailable, the following formula may be used:

$$\begin{array}{l}\text{Head Loss}\\ \text{per Foot}\end{array} = \left[\frac{V_e}{(1.318)(C)(R^{.63})}\right]^{1.852}$$

where:

V_e = velocity in the pipe = Q/A

Q = flow

A = pipe's cross-section = $\pi D^2/4$

R = hydraulic radius = A/wetted perimeter
wetted perimeter = πD

C = friction loss

CHAPTER IV

MECHANICAL ENERGY GENERATION

Water Wheels

> "Every machine is an individual. A turbine is a symphony of noise. You listen. You know if something is missing. Being able to listen to a waterwheel is something that is not in the books..."
>
> Mark Quallen

Water wheels have played a very important role through the centuries in producing mechanical power for mills. For small streams with variable flow, low head and non-freezing temperatures, the waterwheel can be the best choice over an expensive turbine for producing lower ranges of kilowatts. Economical on-site construction and minimal maintenance are additional advantages. A disadvantage is the amount of gearing required to increase the 6-20 rpm of the waterwheel to the 1500 rpm required for a generator.

Contemporary waterwheels are virtually identical in construction to their historical counterparts. Of the four types of vertical wheels, touched upon earlier in this report in a historical context, the overshot and the undershot are the most common types from a point of view of efficiency.

The overshot wheel reaches the maximum efficiency for waterwheels of 60-75%. Water travels down a flume and enters the buckets at the top of the wheel. The weight of the water propels the wheel and power output can be controlled by controlling the water with a sluice gate. The overshot wheel's upper limit of head is about 30 feet.

The undershot wheel makes use of straight paddles and is operated by water flowing beneath the wheel. A head as low as 1 foot is sufficient. Efficiency is only about 25% with a minimum wheel diameter of 15 feet. (See Figure 10).

The Pitchback, or Poncelet, wheel is an improvement of the undershot wheel employing curved blades to increase efficiency but requiring concrete breastwork fitted close to the wheel to hold water in the buckets. Minimum diameter is 14 feet and efficiency is 40-60%.

The breastwheel is a variation of the Poncelet in which the concrete breastwork is builtup higher to allow water to enter just below the top of the wheel. The wheel's diameter should be equal or less than three times the head. Efficiency is 40-65% (Terry 1980). See Figures 11-13.

In designing a waterwheel, the output energy from the wheel may be calculated with the use of the following equation (McGuigan 1978).

$$\text{output (KW)} = \frac{D \times B \times B_{no} \times \text{rpm} \times 0.65}{708}$$

Fig. 10. An operational overshot wheel in Easley, South Carolina (December 1980).

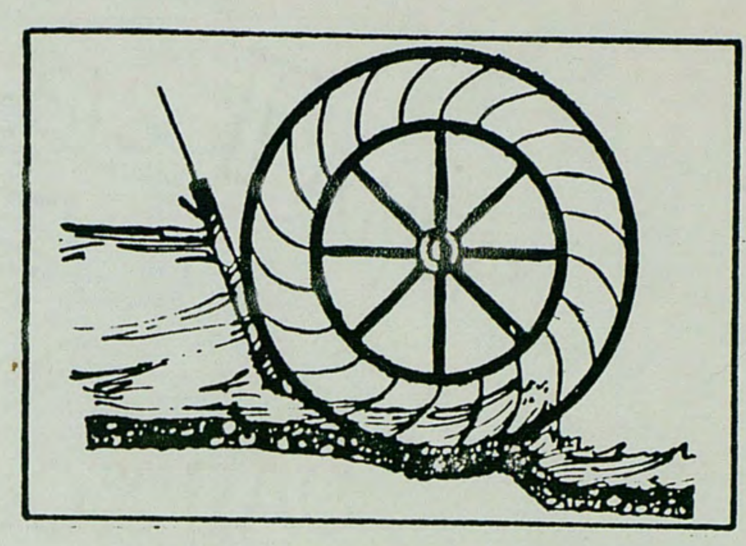


Fig. 11. Poncelet Wheel.

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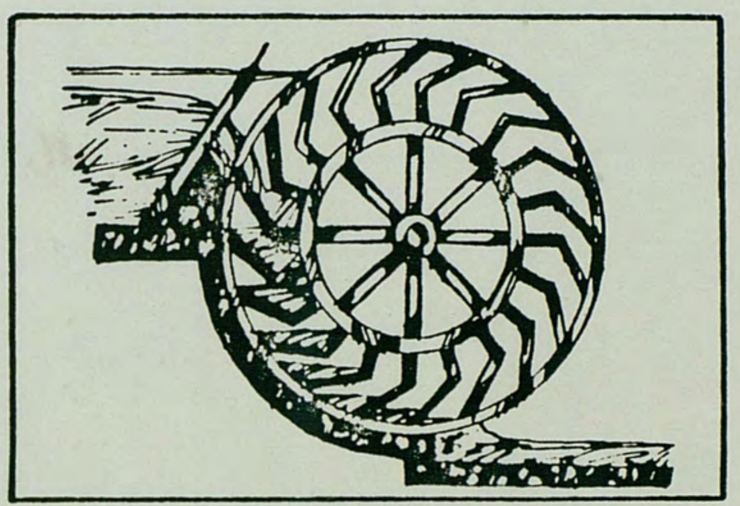


Fig. 12. Breast Wheel.

figure 4

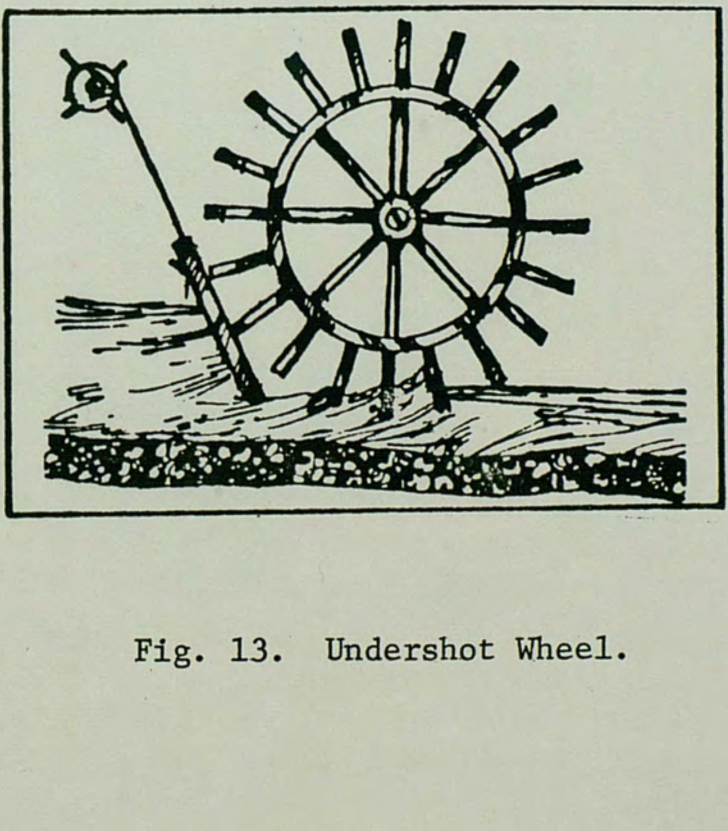


Fig. 13. Undershot Wheel.

figure 2

where:

D = wheel diameter from bucket center

B = working bucket capacity (0.7 of total capacity approximately)

B_{no} = number of buckets

rpm = revolutions per minute

0.65 = efficiency factor

708 = KW conversion factor

Turbines for Micro-Hydro Plants

With the ever-increasing demand for electricity, there has been a strong need for better turbines. Throughout their 250 year history, they have steadily become larger, faster, and far more efficient.

When working in the field of micro-hydropower, it is necessary to apply the technology of large turbines to small turbines. In doing this, there is a considerable challenge in trying to maintain the same high efficiency and high speed.

The principals of the turbine are in a large part based on the works of the 18th century mathematician, L. Euler. His theories lead other scientists like France's Burdin and Foureyron to the understanding that a turbine's efficiency would be related to the degree to which water could contact its blades with a free shock entry, and exit the unit with a minimum velocity. The following Figure 14 shows the relationships between the different variables involved in the design of a radial flow hydraulic turbine.

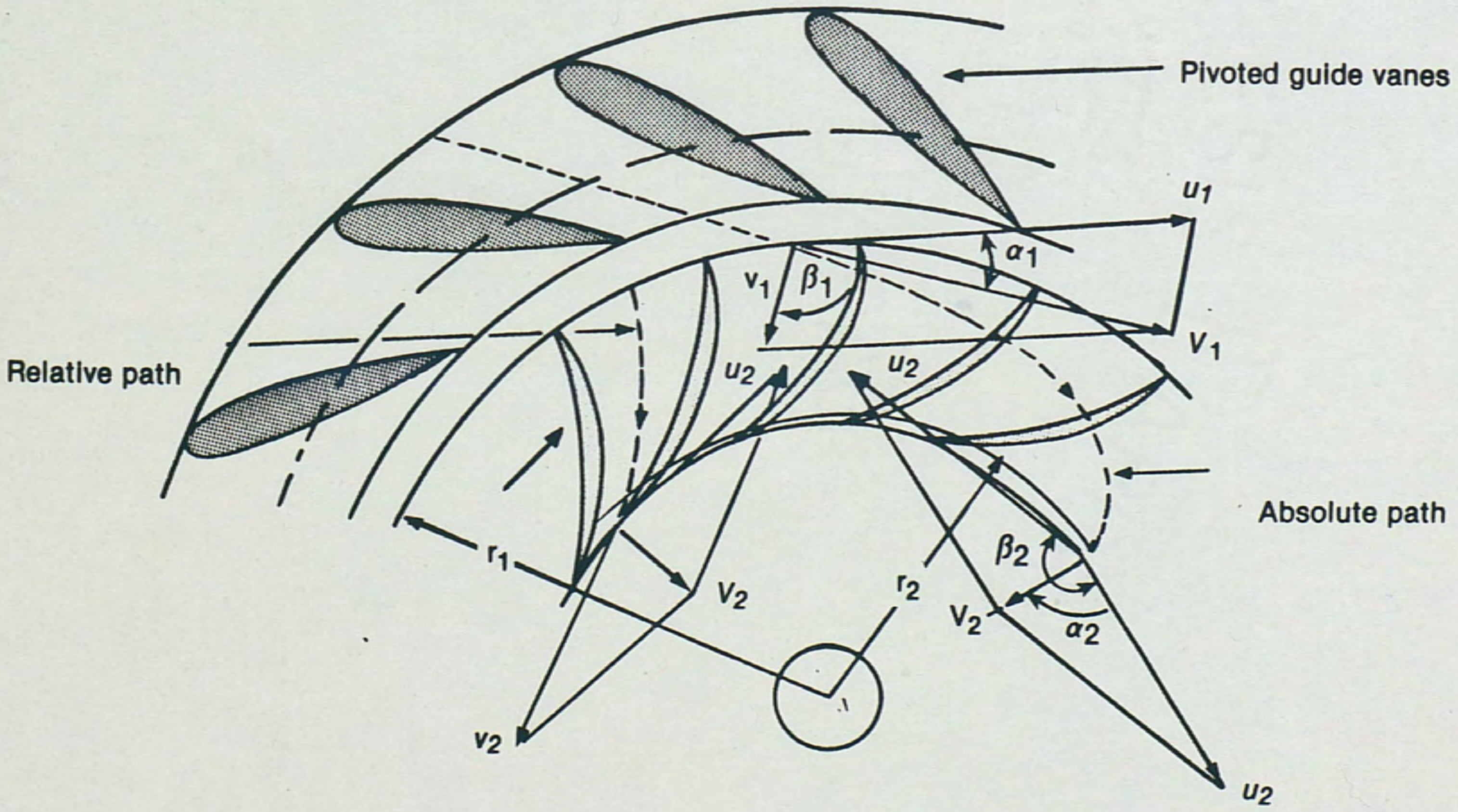


Fig. 14. Radial flow hydraulic turbine. Adapted from Daugherty and Francini.

The studies of Euler demonstrated that the torque on the runner of a turbine can be defined as the difference between the rate of angular momentum entering the runner and that exiting. They also showed that the power developed is proportional to torque and periphery speed (Arndt 1980).

Type of Turbines

There are two types of turbines: impulse and reaction. The inpulse turbine converts the available head to kinetic energy at atmospheric pressure. The reaction turbine, on the other hand, is submerged in water and utilizes the pressure and the available head.

Impulse Turbines

There are several modifications of the impulse turbine. One of these variations is the Pelton Impulse Wheel. It was created by L. Pelton in 1880. This wheel relies on the impact of moving water upon curved buckets. It is used for high heads that are at least 50 feet in height. Figures 15 and 16 show the Pelton Wheel which will be installed to produce 17 KW using 135 feet head.

The water is carried by a pressure pipeline which ends in a nozzle. The nozzle has a circular cross-section that becomes increasingly narrower. In that the quantity of water passing through any given point is always the same, the water must increase in speed as its conduit becomes smaller.

Figs. 15 and 16. Pelton Wheel.

One or two jets can be aimed at the turbine. When producing 10-20 KW, approximately 84% efficiency can be expected. If producing larger amounts of electricity, up to 93% efficiency can be obtained (McGuigan 1978).

It is possible to optimize the working of an impulse wheel by optimizing the power available in the jet. This force can be determined by applying the following formula:

$$Pj = \gamma Q \frac{V_j^{\,2}}{2g} = \gamma \pi dj^2 \frac{V_j^{\,3}}{8g}$$

where:

Pj = power of the jet

V_j = the velocity

dj = the diameter

The above relationship shows that the power of the jet depends on the diameter of the jet and of the penstock. When the water flow increases, losses in the penstock will increase and the velocity of the jet (V_j) will decrease (example plotted in Figure 17).

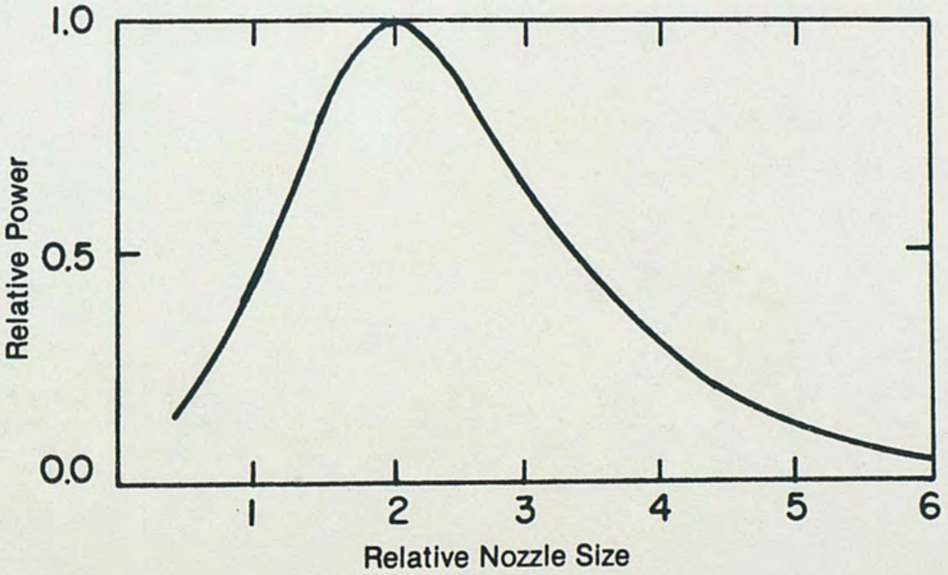


Fig. 17. Pelton Wheel installation.

Optimizing the utilization of the available head also depends on the velocity of the water as it leaves the turbine. For the most efficient results, the water should leave the turbine at zero velocity. Theoretically, this occurs when the peripheral speed of the turbine is 1/2 of the jet's velocity. In actuality, though, optimum power is reached at a speed coefficient ϕ something less than 0.5.

$$\phi = \frac{U_1}{\sqrt{2gH}}$$

or

$$\text{runner rim speed} = 0.5\sqrt{2gH}$$

and

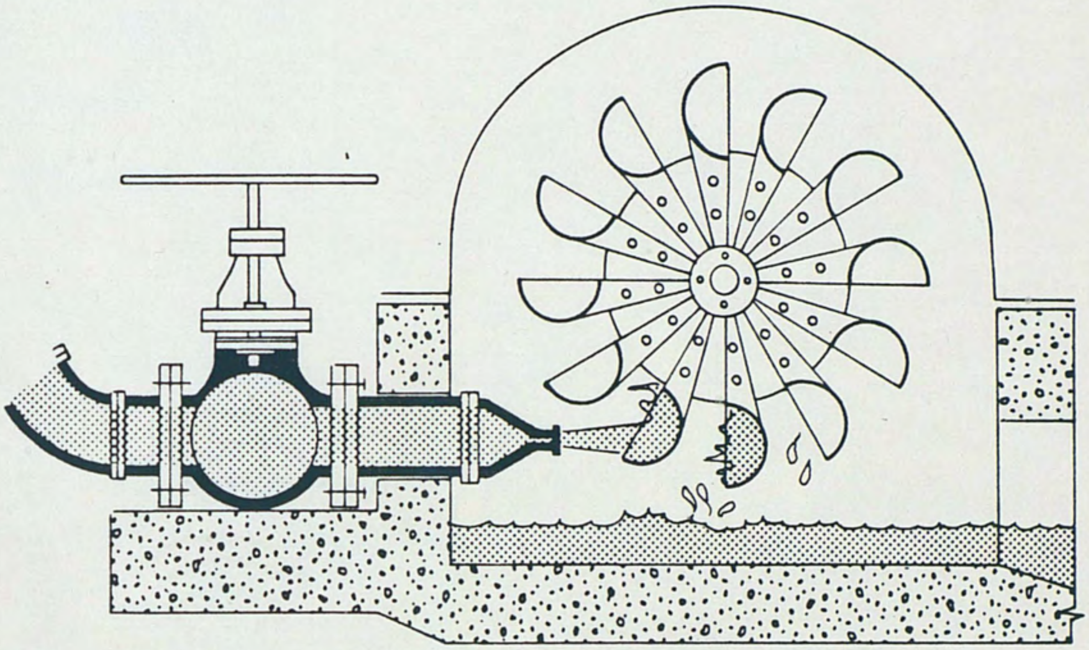
$$\text{rpm} = \frac{\text{rim speed}}{\text{circumference}}$$

The specific velocity of the wheel is a function of the wheel's diameter. For impulse wheels, the following equation can be applied.

$$Ns = 1.3\,\frac{dj}{D}$$

Actual values of dj/D for Pelton Wheels usually range between 0.04 and 0.1. This implies that Ns ranges between 0.05 and 0.13. See Figure 18 for diagram of the Pelton Wheel.

Another type of impulse turbine is the Turgo Wheel. It was designed in 1920 by E. Crewdson. Its shape resembles that of a fan blade. The water enters the nozzle which faces the runner at an angle.



⑤

Fig. 18. The water jet streams out of the nozzle and strikes the curved buckets of the wheel.

The Turgo Wheel is generally more efficient than the Pelton Wheel because it can produce an equal amount of power with a smaller diameter that moves at a higher speed. Its minimum runner to jet ratio is 4:1.

The formulas applied for the optimization of the Pelton Wheels are also applicable to Turgo units. See Figure 19 for diagram of the Turgo Wheel versus the Pelton Wheel.

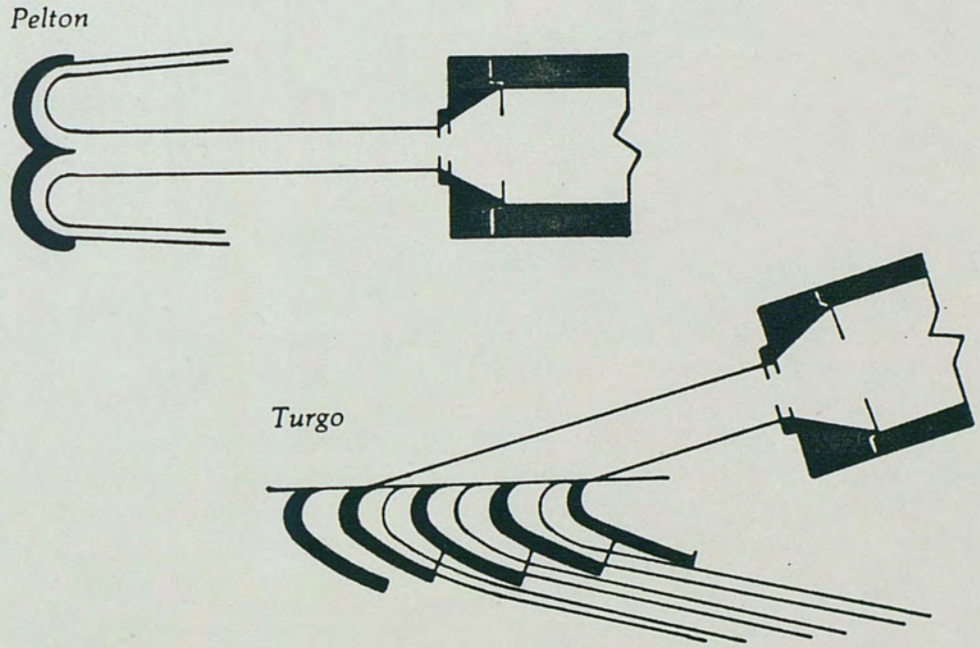


Fig. 19. Turgo and Pelton turbines contrasted. The jet on the Turgo strikes three buckets continuously whereas on the Pelton it strikes only one. A similar speed increasing effect can be had on the Pelton by adding another jet or two.

The third type of impulse turbine is the cross flow or Banki-Mitchell. It was invented by the Australian A.G.M. Mitchell in 1903 and later improved by the Hungarian engineer, Donat Banki around 1918.

The Ossberger Company of Germany has been producing cross flow turbines for the past 50 years. They can be used for heads ranging from 3' to 600' and with flows ranging between 60 and 15000 cfm.

The Banki-Mitchell is a radial impulse turbine. The water from the jet is directed toward the cylindrical runner via a rectangular cross-section. Using its kinetic energy, the water enters into a ring of blades, then onto the barrel shaped runner at the center and finally out through the blades on the other side (Terry 1980).

The main advantage of the cross flow turbine is that it can maintain good efficiency even with wide variations in flow rates. This is especially valuable for micro facilities which oftentimes have considerably different flow rates depending upon the seasons of the year.

Another attribute of this type of turbine is that the machine is basically self-cleaning. Any pieces of trash that might pass through the racks will not become lodged within the unit but will instead be pushed out as the water leaves. In other words, this machine is not subject to cavitation.

The Banki-Mitchell turbine is one of the simplest to manufacture and can be made by local labor. One precaution to take with this type of wheel is to assure that it is installed above the tail water because if the wheel is flooded, its efficiency will be reduced significantly. A draft tube can be placed beneath the turbine in order to create downstream suction and increase head.

Figure 20 shows the details of a 12" Mitchell runner and Figure 21 shows the details of an appropriate nozzle for this particular unit (Stoner 1974).

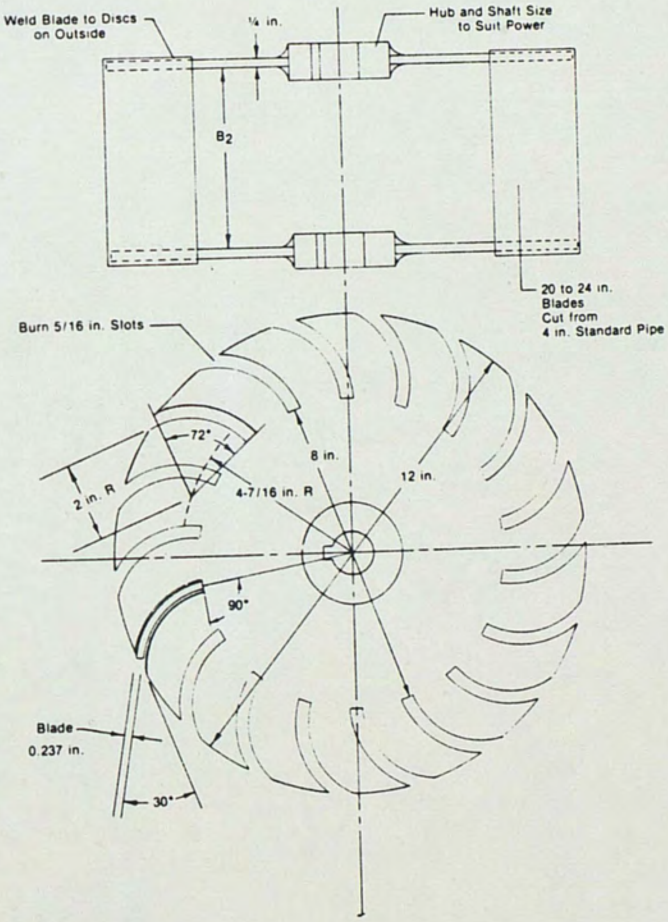


Fig. 20. Detail of Mitchell runner, 12 inch size.

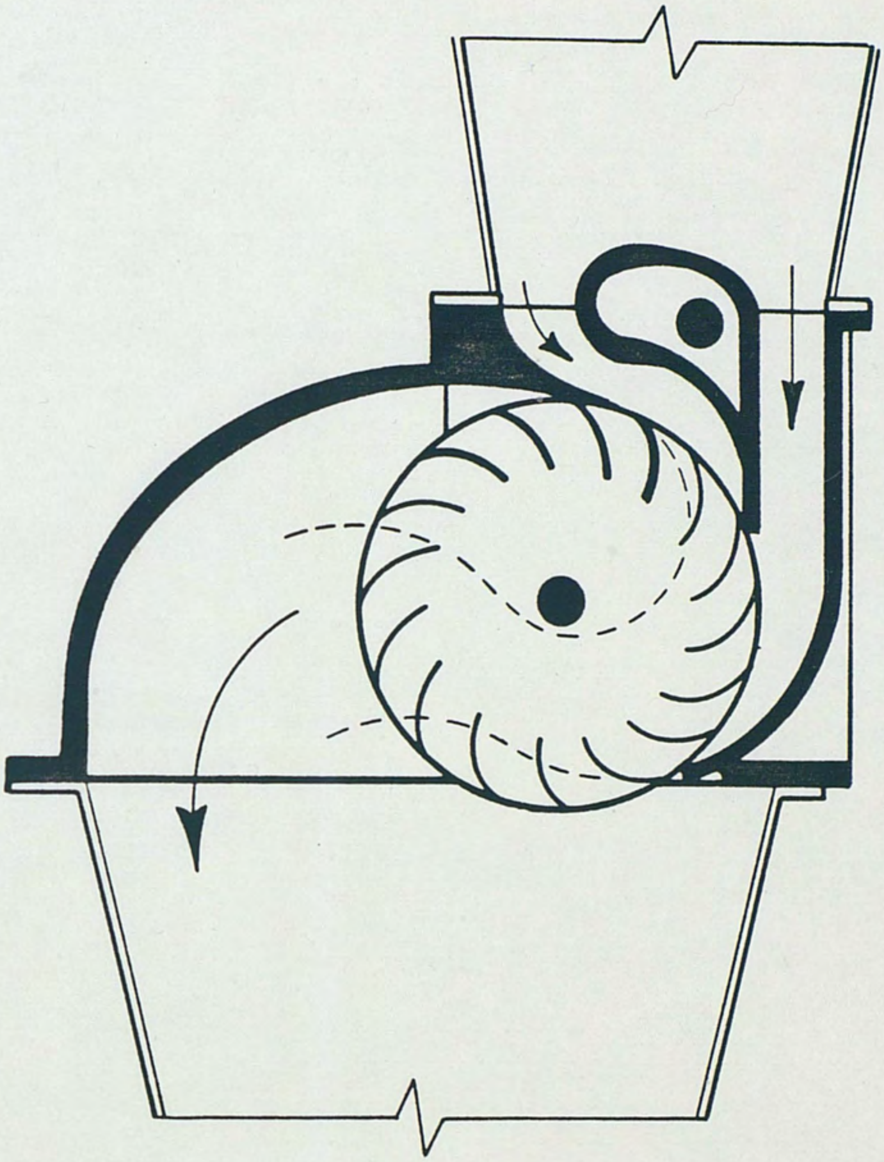


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Fig. 21. The cross flow turbine is split to facilitate flow-governing of incoming water.

Reaction Turbines

In a reaction turbine, the pressure drop that takes place in the rotating passage moves the runner. Rather than water velocity driving the runner, water pressure does the work. This means that the entire flow passage from the inlet to discharge at the tail water must be completely filled.

Determining the optimum specific speed for a reaction turbine is more complicated than in the case of the impulse turbine due to the many extra variables affecting its efficiency. For example, the turbine must be properly positioned above the tailwater to reduce head loss at discharge. It is essential to follow individual manufacturer's recommendations on installation.

The Francis Turbine was designed by James B. Francis. Guide vanes around its periphery direct the falling water into the runner which is placed on a vertical axis (see Figures 22 and 23).

Low head application Francis runners have an inlet diameter smaller than the discharge diameter and entrance height is increased substantially to provide a greater entrance area. For medium head applications the inlet and discharge diameters are kept nearly equal. High head runners are characterized by a large inlet diameter with low entrance height and a smaller discharge diameter.

Originally, the low head versions were designed with low speed runners, which were not susceptible to cavitation, provided their passageways and buckets were properly shaped. Later,

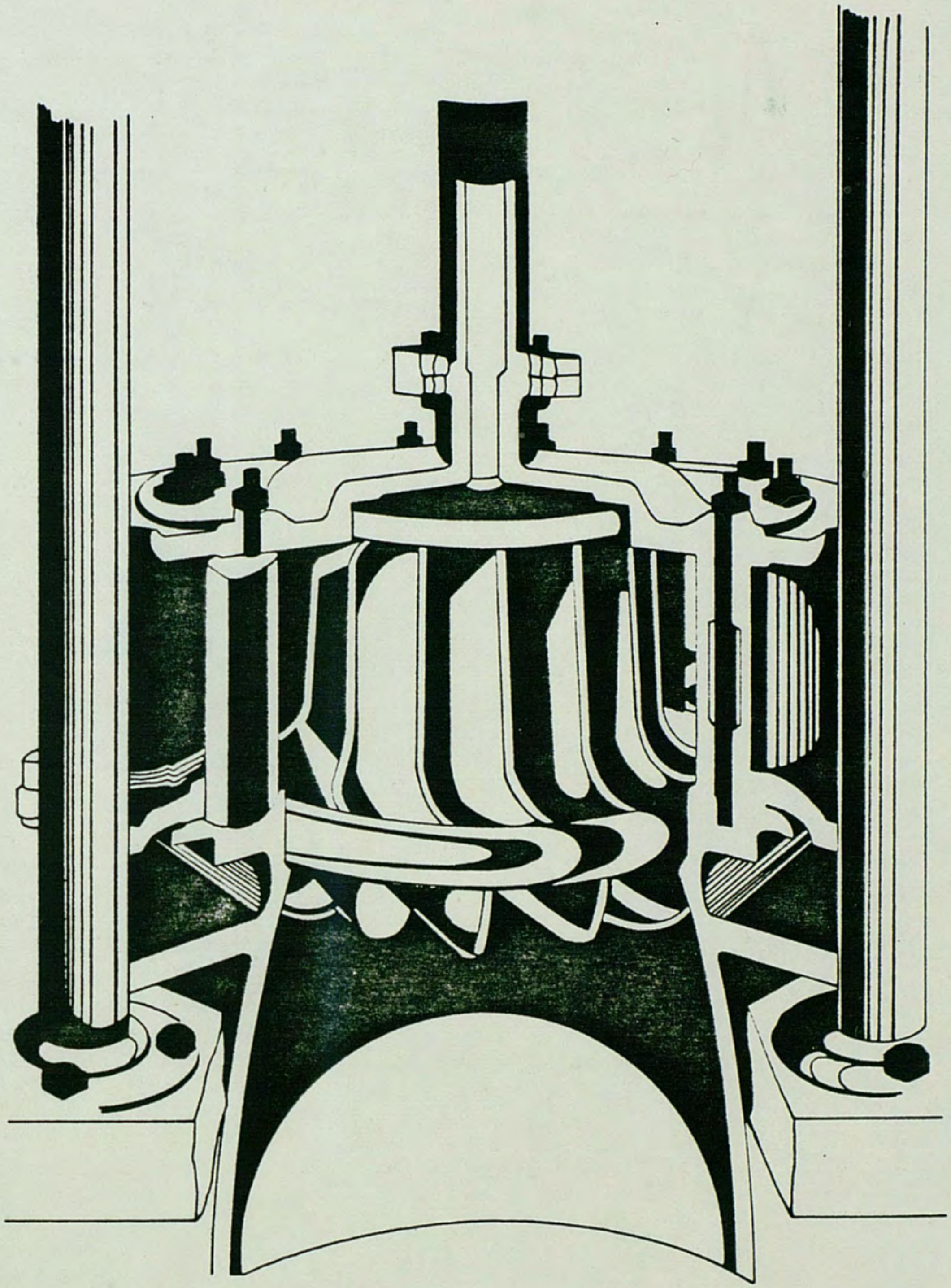

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Fig. 22. Francis turbine in open chamber with guide vanes and draft channel.

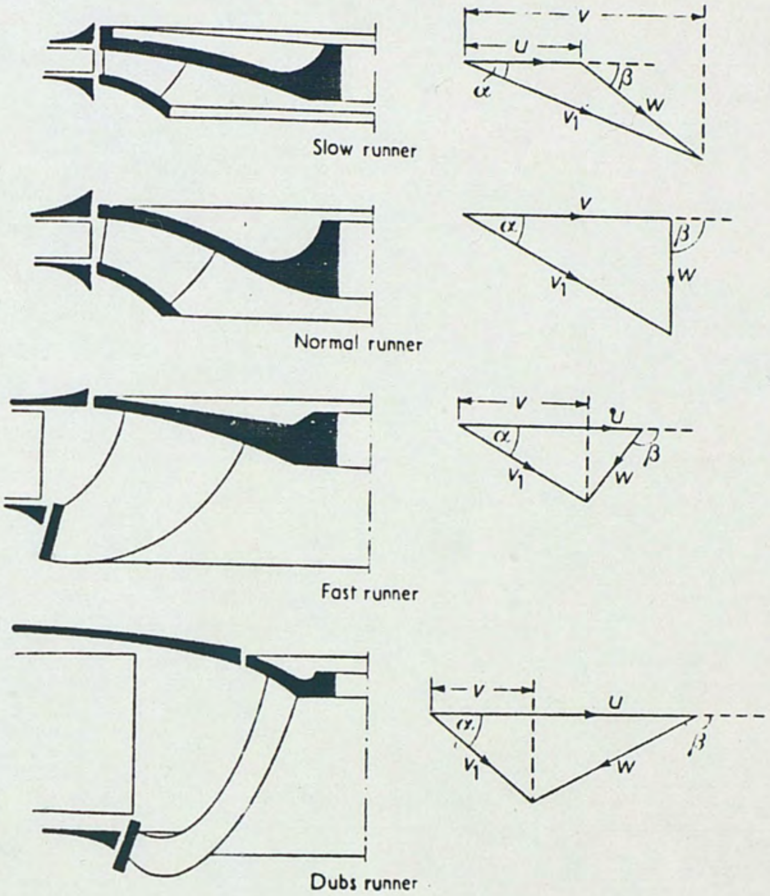


Fig. 23. Various shapes of Francis Turbine runners, with velocity triangles according to variation of specific speed, Ns. Slow runner: Ns = 13.5 to 27, α = 15 to 25 degrees, $\beta < 90$ degrees. Normal runner: Ns = 27 to 40.5, α = 25 to 35 degree, β = 90 degrees. Fast runner: Ns = 40.5 to 67.5, α = 35 degrees, $\beta > 90$ degrees. Dubs runner: Ns = 63 to 117, $\alpha < 90$ degrees, $\beta \gg$ 90 degrees.

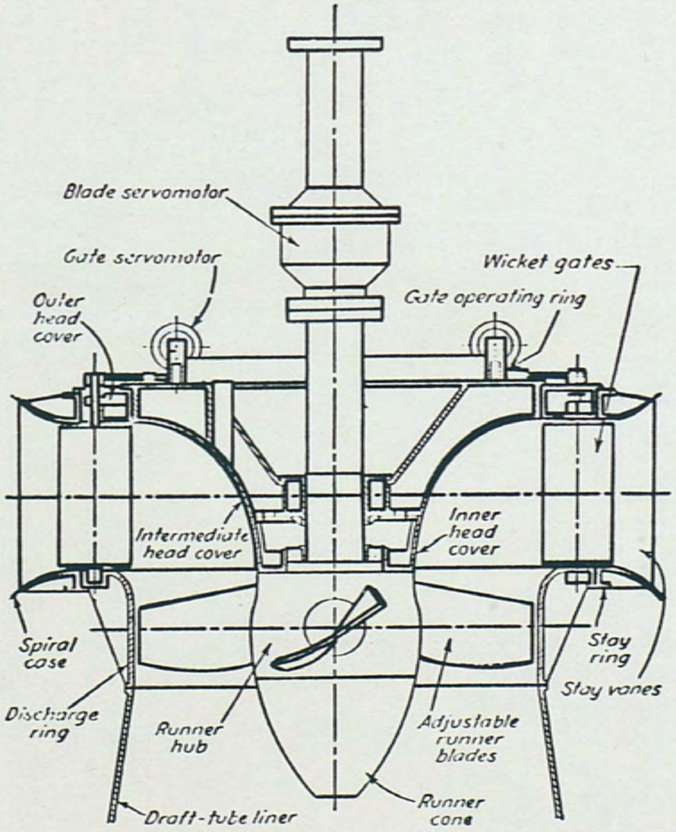


Fig. 24. Smith-Kaplan axial-flow turbine with adjustable-pitch runner blades, $N_s \simeq 3.4$

9

higher speed runners were adopted, increasing runner output for a given head, but also increasing the danger of damage by cavitation. The problems may be reduced by setting a high speed runner closer to the tailwater elevation.

The propeller turbine uses a runner design similar to that of the Francis units for mixed flows and medium heads. Where the flow is axial, however, the design changes considerably and the result is a high speed reaction turbine useful for low heads from 3 to 30 feet. The number of propeller blades is generally fewer than that of any of the Francis designs. This provides a higher speed and greater output, but also results in greater blade load, making the problem of cavitation more critical.

A fixed blade propeller works efficiently in a case where the water flow is constant, but this rarely occurs in a micro system. The Kaplan Turbine (Figure 24) with adjustable blades and wicket gates is presently the best technological solution to the problem of the variable axial flow situation. The high cost of this grade of technology, however, has so far prevented it from becoming a useful tool in actual micro-hydro applications. Other variations of the propeller turbine concept include the tube, the bulb and staflow.

Use of a Pump as a Turbine

Now being studied is the possibility of using small pumps as small turbines. The advantage of these are that pumps are readily available throughout the world and that their technology is simple enough that local designers or workers can easily deal with their conversion.

The working of a hydro-turbine can be divided into three stages:

Part 1: where the water is received at the bottom of the net head and is then distributed

Part 2: the entrance (nozzle) where the water pressure is converted to velocity energy and the flow is sent in a predetermined direction

The converting formula is: $V = \sqrt{2gh}$

where: g = gravity

h = net head

Part 3: the impeller or number where the velocity is minimized as much as possible. This deceleration of velocity is accomplished by changing the flow's direction as it pushes against the moving blades of the runner. In an impulse turbine the velocity of the water jet is almost twice the velocity of the bucket. When the bucket is moving away from the stream of water at normal speed and when the velocity of the rebounding water equals the velocity of the entering water, the water velocity of the rebounding water also approaches zero.

A pump works in three stages, like a turbine, except that they operate in reverse:

Part 1: a supply of water with a sufficient net head to assure that the flow will continue hitting the runner at the same time that the water is discharged.

Part 2: consists of an impeller that accelerates the water by centrifugal force. This part acts exactly the opposite as the turbine's impeller where the water is decelerated by the runner.

Part 3: consists of a gate where the velocity energy is converted to head pressure. Ignoring efficiencies we can apply the same formula:

$$H = \frac{V^2}{2g}$$

NOTE: This system is not recommended where the head is above 48 feet (Grover 1980). Figure 25 shows a diagram of a centrifugal pump. Table 7 gives the different types of turbines and their efficiencies.

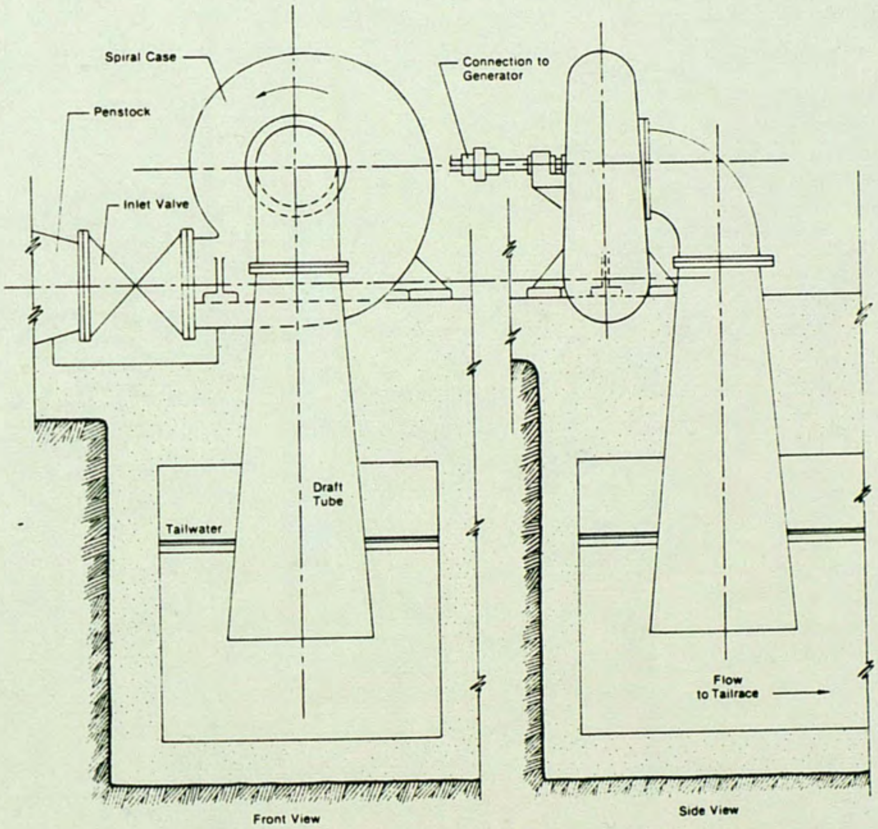


Fig. 25. Centrifugal pump which, with reversed rotation, can function as a water turbine.

TABLE 7

TURBINES AND THEIR EFFICIENCIES

Turbine	Head (ft)	Flow (cfs)	Efficiency
Pelton (Turgo)	20-80 or more	less than 10	93%
Cross Flow	10-200	less than 200	70-88%
Francis	10	10 or higher	90%
Propeller	less than 50	10 or higher	85%
Kaplan (angle changed)	less than 50	10 or higher	85%

CHAPTER V

GENERATING ELECTRICITY

Electricity is one of man's most beneficial forms of energy. It is produced by physical attractions that are generally independent of gravitational and short-range nuclear forces.

Electricity is created when electrons move. This can occur when an incoming electron or light pulse knocks another electron out of its orbit or when electrons come in contact with a magnetic field.

In 1831, Michael Faraday discovered that if he moved a magnet in and out of a coil of copper wire, a small electric current could be detected running through the wire (Syrocki 1960). With further experimentation, Faraday showed how electrical energy was capable of being transformed into mechanical energy and how the invisible electric current could be used to turn shafts at high speeds (McGraw-Hill, Encyclopedia of Science).

Faraday's findings led to the works of Ampere and Oersted who developed the principles upon which most electric motors and generators operate.

Today, the field of electricity is very technical. People who are going to generate their own electricity with micro-hydro projects should consult with persons who have experience with electricity. It is also advisable that designers themselves become familiar with basic electrical concepts and terminology.

The term voltage, for example, represents the measurement of the pressure with which electricity is supplied. The higher the voltage, the easier electricity can pass through materials, the farther it can travel, and the more dangerous it is to work with. Human contact with electricity over 50 volts can be quite deadly (McLaughlin 1977).

Amperage is used to measure the amount of electricity passing through a wire and into a piece of equipment. It can be calculated by dividing an appliance's wattage (which is constant) by the line's voltage. The important thing to keep in mind is that the wire used must be thick enough for the amperage which will be carried.

The power required to operate an electric device is measured in terms of wattage. In the United States, utility companies charge their customers per kilowatt-hour, which is equivalent to the amount of energy consumed by a 1000 watt appliance in one hour.

Power Requirements

In order to get the most out of a micro-hydropower plant investment, it is necessary to estimate how much electricity will be consumed and how much power can be generated.

If the electricity supplied is expected to be more than that which will be required, it is possible to sell the excess amount to a local utility company or to a neighbor. If this is not feasible, though, it may be more economical to reduce the scale of the original design.

To get a general idea of how much power is required by various household appliances, refer to Table 8. Table 9 shows the wattage for different motors and Table 10 gives some of the agricultural power demands (McLaughlin 1977).

Designers must be aware of the peak loads and limitations of the electrical system. A well designed system should provide enough power to start 6 machines at the same time (Kuecken 1981).

Motors and Generators

Practically any machine that operates as a motor can be converted to a generator if the shaft of the device is spun faster than it would normally turn as a motor. In doing this, the generator's counter electromotive force (emf) will increase beyond the voltage of the line and will, in turn, supply the line with power (Kuecken 1981).

Generators can produce direct or alternating current. Those which produce alternating current (AC) are referred to as alternators.

Alternating current reverses direction in a circuit at regular intervals. The number of times this alternating cycle is repeated in a second is called the frequency which is measured in Hertz.

TABLE 8

TYPICAL HOUSEHOLD APPLIANCE LOADS

APPLIANCE	POWER (WATTS)	AVG. HOURS USE/MO.	TOTAL POWER CONSUMP. KW HR/MO.
Blender	600	3	2
Car Block Heater	450	300	135
Clock	2	720	1
Clothes Dryer	4600	19	87
Coffee Maker	600-900	12	7-11
Electric Blanket	200	80	16
Fan (kitchen)	250	30	8
Freezer (chest, 15 cu ft).	350	240	84
Hair Dryer (hand-held)	400	5	2
Hi-Fi (tube type)	115	120	14
Hi-Fi (solid state)	30	120	4
Iron	1100	12	13
Light (60-Watt)	60	120	7
Light (100-Watt)	100	90	9
Lights (4 extra, 75-Watt)	225	120	27
Light (fluorescent, 4')	50	240	12
Mixer	124	6	1
Radio (tube type)	80	120	10
Radio (solid state)	50	120	6
Refrig. (standard, 14 cu ft)	300	200	60
Refrig. (frost free, 14 cu ft)	360	500	180
Sewing Machine	100	10	1
Toaster	1150	4	5
TV (black & white)	255	120	31
TV (color)	350	120	42
Washing Machine	700	12	8
Water Heater (40-gal)	4500	87	392
Vacuum Cleaner	750	10	8

* * * * * * * * * * *

Shop Equipment:			
Water Pump (½ hp)	460	44	20
Shop Drill (¼", 1/6 hp)	250	2	.5
Skill Saw (1 hp)	1000	6	6
Table Saw (1 hp)	1000	4	4
Lathe (½ hp)	460	2	1

17KW

TABLE 9

MOTOR WATTAGES

Motor HP	Starting Watts	Running Watts
1/6	900	200
1/4	1,300	300
1/3	1,500	360
1/2	2,200	520
3/4	3,400	775
1	4,000	1,000

TABLE 10

POWER DEMANDS IN AGRICULTURE

Application	Approximate Wattage	Energy Demand (kwh)
Feed grinding	1-10,000	1 per 200 lb feed
Grain drying (heated air)	3-10,000	6 per ton grain
Grain elevating	300- 3,000	4 per 1000 bushel
Hay curing (heated air)	3- 7,000	50 per ton
Milking machine	500- 2,000	1-1/2 per cow/month
Silo unloading	300- 500	1/2 per ton
Brooder	125- 1,000	0.8 per chick/month
Incubator		0.2 per egg/month

In the United States, most appliances run on single phase AC current and a frequency of 60 Hertz (McGuigan 1978). Table 11 shows the number of magnetic poles and the rotational speed required for an alternator to generate 60 Hertz frequency.

TABLE 11

NUMBER OF MAGNETIC POLES AND THE ROTATIONAL SPEED REQUIRED FOR AN ALTERNATOR TO GENERATE 60 HERTZ

Number of Poles	Speed for 60 Hertz Output (rpm)
2	3,600
4	1,800
6	1,200
8	900
10	720

One of the problems with creating AC current is that the electricity generated cannot be stored in a practical way. Because of this, it is necessary to select a generator which is capable of meeting the peak electrical needs.

There exists on the market today a few self-exited 1800 rpm (4 pole) alternators for micro-hydro systems. These kinds of generators, though, can be damaged by being sped too fast, so it is advisable that they be connected to some kind of speed control or governor (Schoonmaker 1981).

The primary advantage of choosing a DC generator is that its direct current can be stored in batteries. This becomes quite beneficial in those times when there is less electricity being generated than needed. DC equipment is available for the production of 12, 24, 32, 36, 48 or 110 volts.

Direct current (DC) always travels in the same direction. It is normally considered to flow from the positive terminal of a generator or battery to the negative terminal. Its voltage and amperage usually stay steady as the current completes its circuit.

In order to change direct current into alternating current, a static inverter can be employed. There is presently an inverter for sale which does not necessitate expensive governors or batteries. Known as the Gemini Syncronous inverter, it is able to connect the generator to the utility company's grid and, in doing so, applies a 60 Hz wave form in phase to the micro facility's direct current (Schoonmaker 1981).

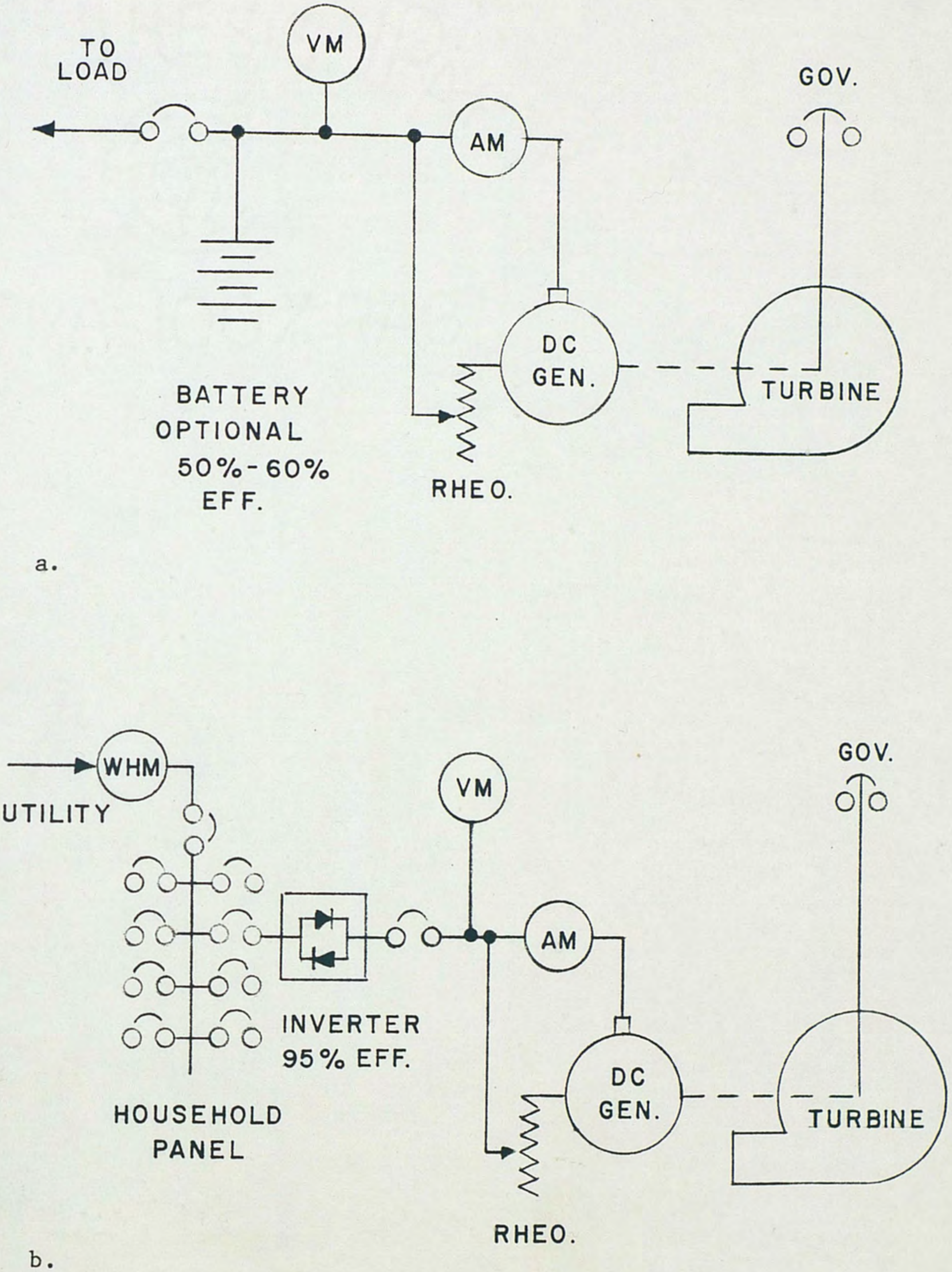
Single Phase Induction as a Generator

If the micro power plant can be connected to the public utility, it is possible to use an induction motor generator. This type of generator requires alternating line voltage at its terminals before it can produce electricity.

The advantage of an induction motor is that it does not have an exact rpm speed to produce a 60 Hz current. It is designed to keep up with the line's current at various speeds.

Usually, the motor would be set to run at about 110% of syncronous (for example, 1.1 x 1800 rpm or 1980 rpm). With a 5% tolerance variation, it could provide a useful output from between 1900 to 2000 rpm. This relatively high tolerance is beneficial because it is not always possible to control the precise speed of the turbine's shaft (Suhre 1980).

The following diagrams show the various circuits between the turbines and the household panels. These have been approved by the Carolina Power and Light Company. (See Figures 26-29.)



a.

b.

Fig. 26. DC Separate load (a) and DC co-generation in parallel (b).

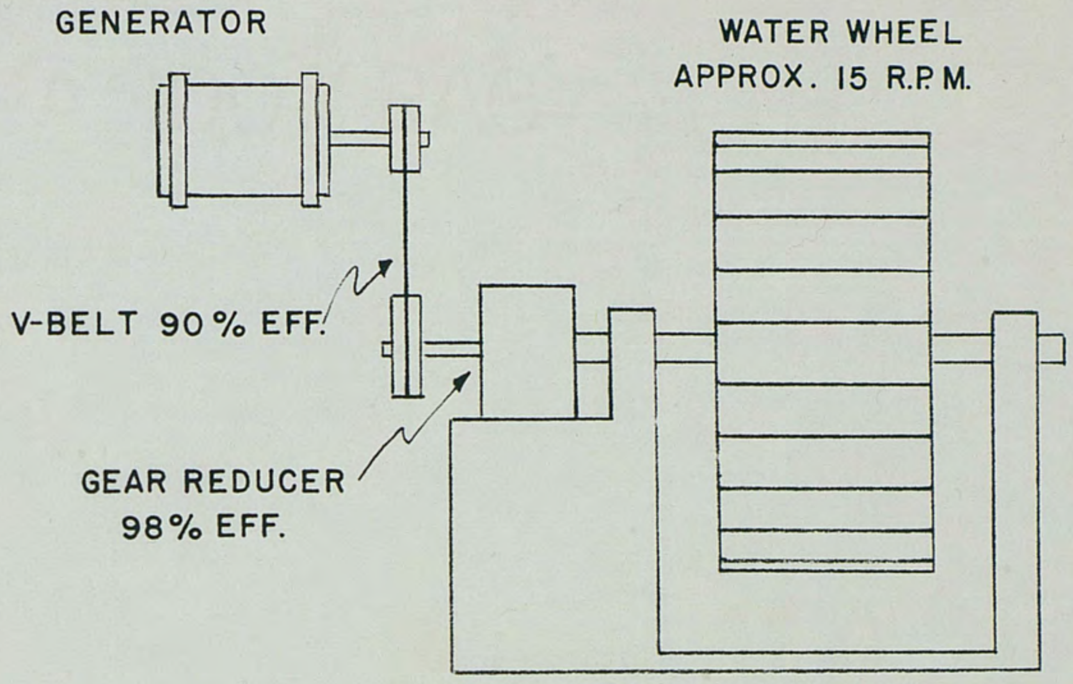


Fig. 27. Connection - water wheel to generator.

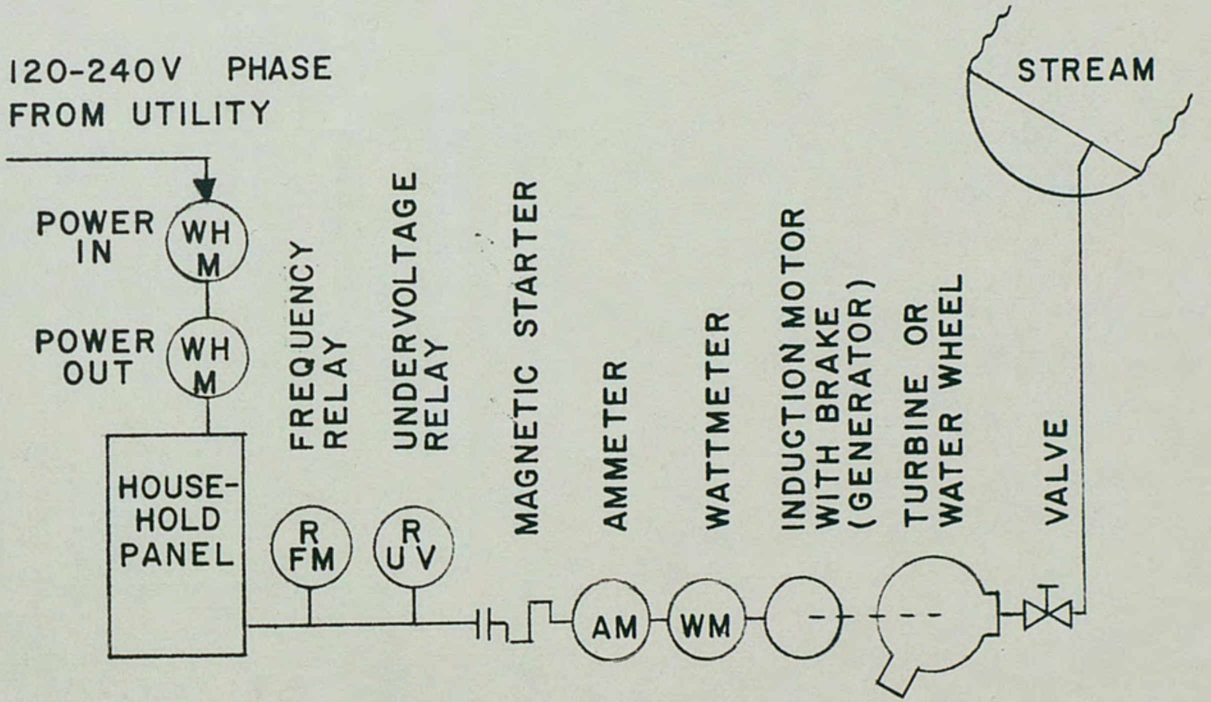
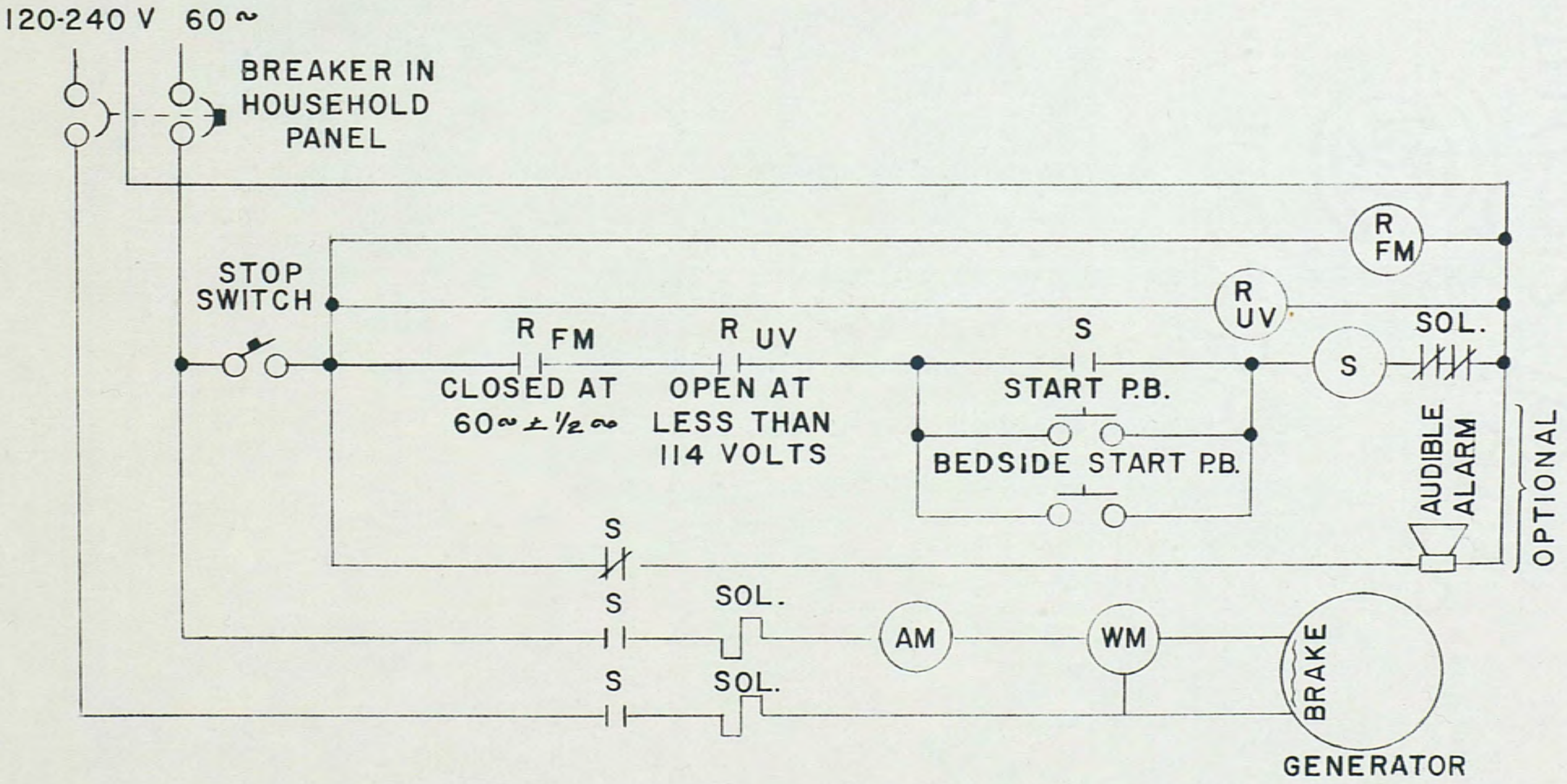


Fig. 28. Single-line diagram.



R_{UV} = UNDER-VOLTAGE RELAY — POTTER & BRUMFIELD CSJ38-70010 — ($ 38)

R_{FM} = FREQUENCY BAND MONITOR — TIME MARK CORP. B-290-B — ($ 92)

S = MAGNETIC STARTER

Fig. 29. Schematic control diagram.

CHAPTER VI

CASE STUDIES OF MICRO AND SMALL HYDROELECTRIC PLANTS IN NORTH AND SOUTH CAROLINA

Case Study #1

In Watauga County, North Carolina, on the Laurel Creek, there is presently a project under construction whose purpose is to demonstrate the feasibility of micro-hydropower technology. The area in which it is located is quite suitable in that the region is mountainous and the rainfall is relatively high (55-80 inches a year).

The program is being directed by one of the leading micro-hydropower advocates in the United States, Dr. Harvard Ayers. It has been funded by a grant from the U.S. Department of Energy.

The facility can be separated into four different parts: the intake structure, the penstock, the turbine-generator system and the electrical system that connects the hydropower to the local utility company. When completed, the unit is expected to generate 17 kilowatts.

The intake structure is located 1600 feet away from the turbine. The difference in elevation is approximately 175 feet. At the intake site, a 1-1/2 foot retainer has been constructed, and thus there will be a certain amount of control over the entry of the water into the penstock (see Figure 30).

Fig. 30. Dam at the intake site (1-1/2 feet).

The actual intake point is off to the side of the stream and the dam. This arrangement in conjunction with a filter screen helps to minimize build-up of debris and siltation.

The 1600' long penstock consists of 8" PVC pipe. The conduit is secured by posts driven into the ground. There are a few bends along the way, which when added to normal friction, should reduce the gross head of 175' to a net head of about 135'.

The system is designed to carry 2.5 cfs of water into the turbine. The turbine is basically a standard Pelton Wheel with a 15-inch diameter. It was cast by Dependable Turbines of Vancouver, British Colombia and it was balanced by Canyon Industries of Deming, Washington.

The runner of the turbine is expected to operate at about 700 rpm which is 80-85% of its theoretical capacity. The water will enter into the turbine through two locally manufactured needle nozzles. Each nozzle will strike the runner at diametrically opposed points with a flow of 1.25 cfs.

The turbine will be connected to a 30 horsepower induction motor-generator by means of a gear up of 2.5 to 1. This will spin the generator at about 1860 rpm and produce 220 volts and 60 Hz alternating current when tied into the local utility grid.

The local utility has approved the entire electrical design. This includes an automatic shut-off system comprised of a series of under and over voltage relays, a cycle variation relay, a reverse power relay and a manual disconnect switch.

Excluding the costs for the transformer and the hookup line, the system is projected to cost $13,100. If the facility produces 17 KW, it will cost approximately $800 per KW to construct which is about half as much as nuclear or coal fired power plants.

The following table (Table 12) shows the estimated costs of this project (Ayers 1981).

TABLE 12

ESTIMATED COSTS OF THE PROJECT

Item	Cost
Dam	$ 2,000
Pipe	4,500
Runner	1,500
Nozzles and housing	1,500
Generator	1,200
Gears	500
Switch gear	300
Control panel	600
Power house	1,000
TOTAL:	$13,100

This particular project does not show labor costs because it is being constructed by people who have volunteered. Their only payment will come in the future when they will receive 25% of the total revenue generated; 50% of the revenue will go to the owner of the property, and the remaining amount will be used for maintenance costs and other research programs.

Case Study #2

Recently, the Department of Energy has been researching the hydroelectric potential and economic feasibility of different sites that already have existing dams. In this case study, nine different sites located in North and South Carolina will be presented. Their names and locations are given in Table 13.

TABLE 13

HYDROELECTRIC POTENTIAL - NORTH AND SOUTH CAROLINA

Site #	Location	
	City	State
1	Randolph #2	NC
2	Fairmont	SC
3	Glendale	SC
4	Berry Shoals	SC
5	Junaluska	NC
6	Stevens	SC
7	Glencoe	NC
8	Woodside	SC
9	Spray	NC

Table 14 shows the values of different parameters for each location. The costs have been based solely on head and capacity data. They represent new construction and do not take into consideration existing equipment or any special site characteristics (Neitzel 1980).

According to the engineers who researched this data, these projects should be adequately profitable because their

TABLE 14

PARAMETRIC VALUES FOR DIFFERENT LOCATIONS

Site	Head (ft)	Average Annual Flow (cfs)	Capacity-KW (86% eff.)	Plant Factor (%)	Average Annual KWH	Invest-ment Costs	Operating Maintenance 2% of total	Benefit Estimate	
								Energy Value (mills/KWH)	Average Energy Value ($.044/KWH)
1	16	278	144	50	631,000	396,000	15,800	41.56	26,200
2	25	87	158.8	50	695,000	388,000	15,500	44.43	30,900
3	25	110	200.7	50	879,000	407,000	16,300	44.43	39,100
4	17	162	201	50	880,000	424,000	17,000	44.3	39,100
5	29	139	307	50	1,345,000	477,000	19,100	41.56	55,900
6	20	192	280.3	50	1,228,000	485,000	19,400	44.43	54,600
7	12	495	453	60	2,381,000	994,000	39,800	40.94	97,500
8	40	276	805.8	50	3,530,000	712,000	28,500	44.43	156,800
9	32	616	1000	50	4,380,000	867,000	34,700	41.56	182,000

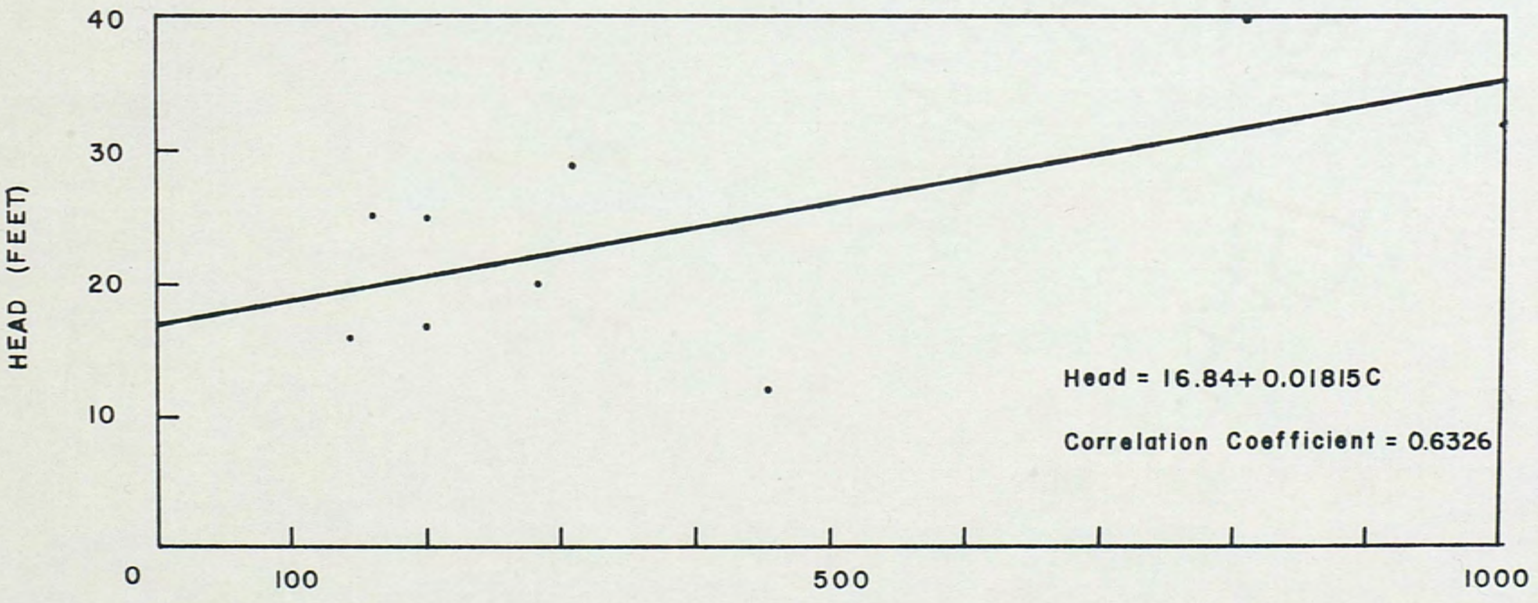
revenue earned is expected to escalate by 8% annually while their operating and maintenance costs should escalate by 6%.

In Graphs 4 through 7, the various heads (ft) average annual flows (cfs), investment costs (turbine, generator and civil work), and average annual energy values are plotted in relationship to the different plant capacities. Each graph also contains the resulting equations for these relationships.

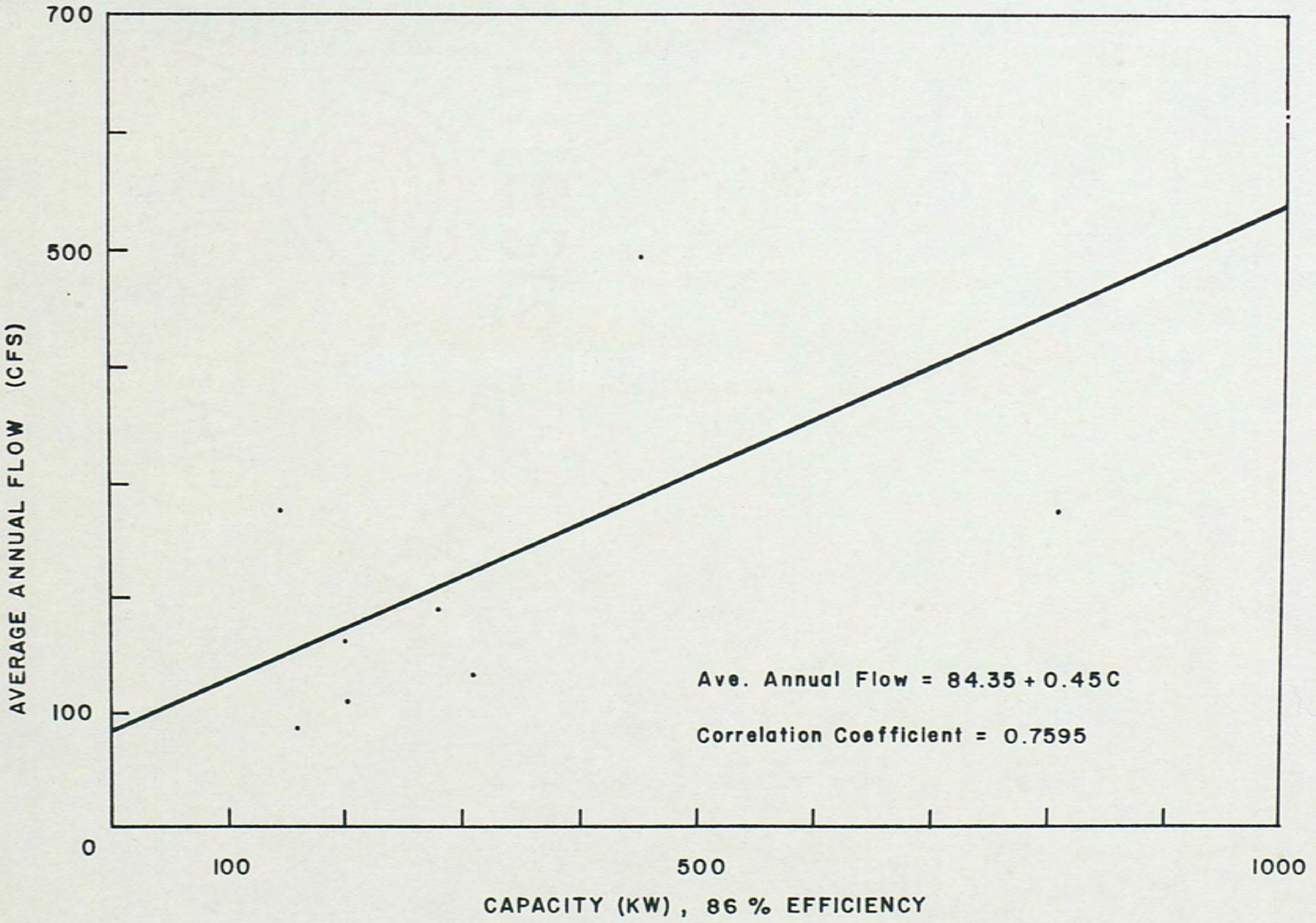
An interesting observation from these graphs is that the Glencoe (location 7) facility in North Carolina is expected to get 453 KW utilizing only 12 feet of head.

Graph 6 shows that the investment cost for this facility is much higher than the average. This is probably because a very sophisticated and costly turbine such as the Kaplan will be employed.

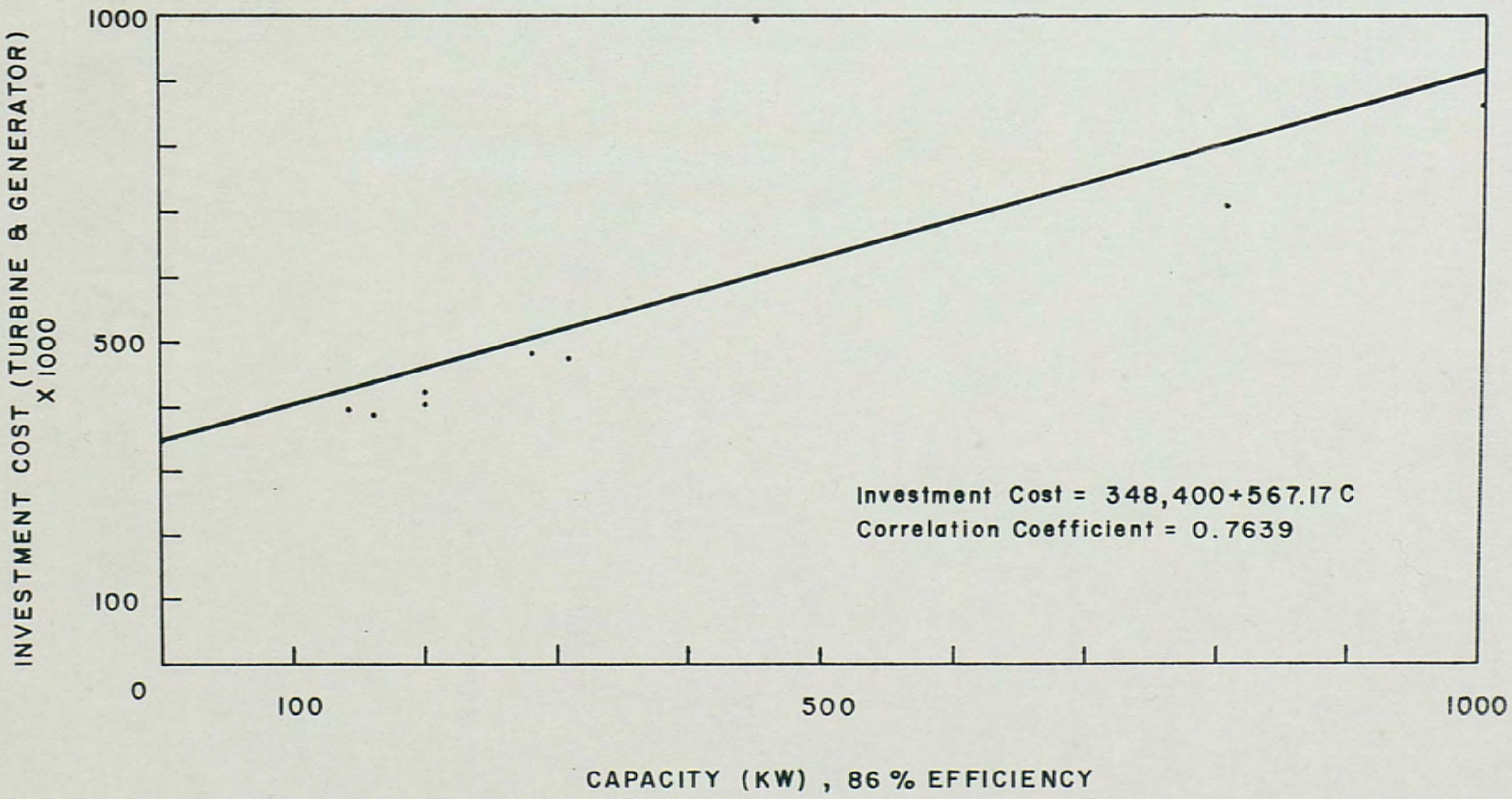
In conclusion, it can be said that small and micro hydro designers should study all of the different economic alternatives. At low head sites, it is possible to generate high amounts of power with sophisticated equipment but may be more feasible to rely on simpler equipment and settle for less electricity.



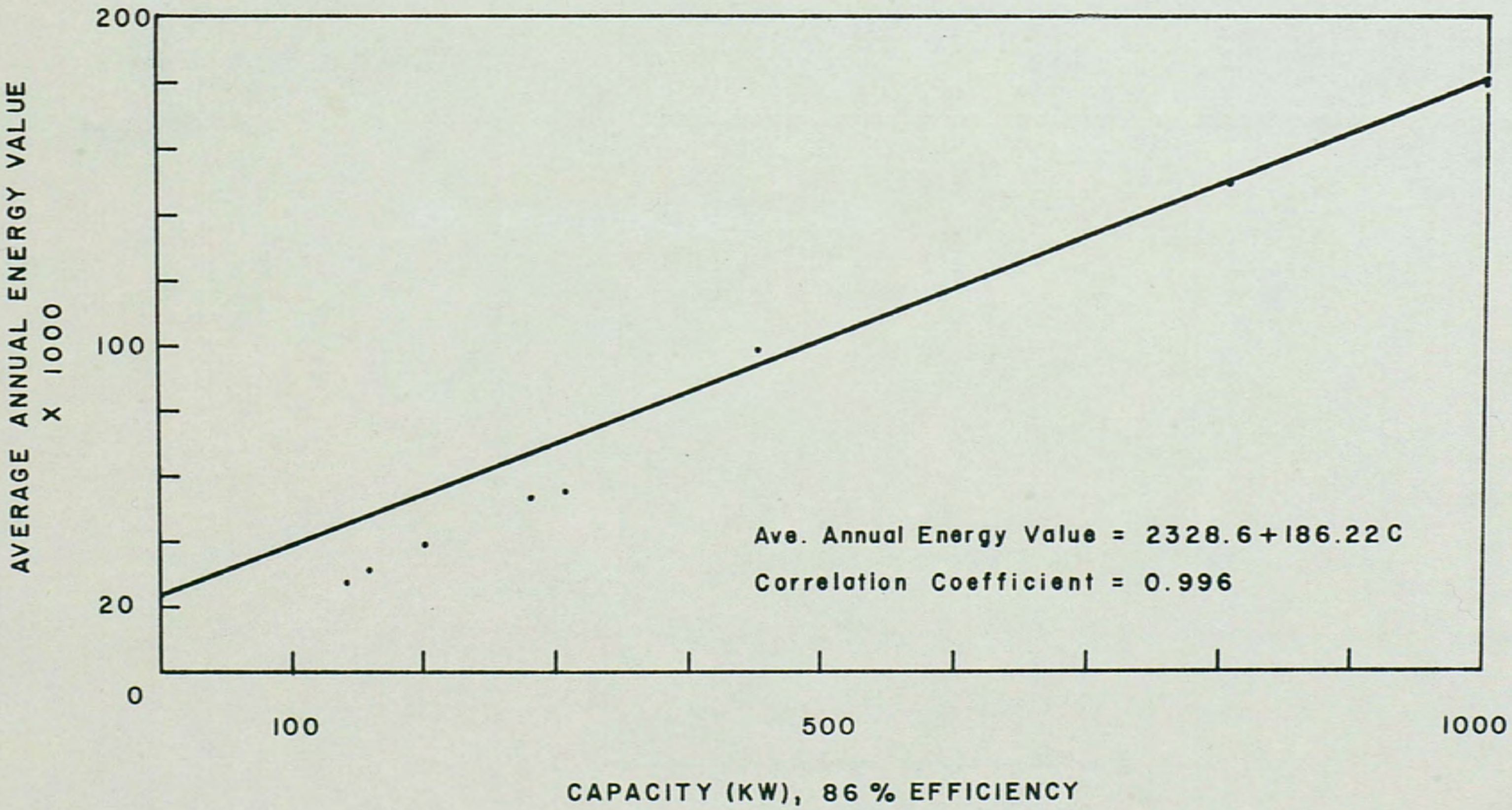
Graph 4. Head and capacity.



Graph 5. Average annual flow and capacity.



Graph 6. Investment cost and capacity.



Graph 7. Average annual energy value and capacity.

CHAPTER VII

ECONOMIC IMPACT

In order to determine the feasibility of a micro-hydro plant, it is necessary to project its costs and revenues or savings in the most accurate way possible.

The economic feasibility of a hydro facility depends largely on where it is being employed. In Massachusetts, for example, a plant that costs $1000/KW is considered to be a worthy investment, while in areas of the world which rely on diesel fuel, $2000/KW is acceptable (Allen 1978).

In general, constructing a micro system costs from $750/KW to $1500/KW. Variations will occur depending on the necessary site work to be completed.

Though initial capital expenditures are high, they can be reduced. It is possible, for example, to supply one's own labor, utilize already existing dams, or take advantage of high head situations (Terry 1980).

Once the true costs are estimated, they can be compared to the probable returns. If the electricity will be sold to a utility company and the project is in the U.S., it will come under the Public Utility Regulatory Act (PURPA) of 1978. This federal law requires that utility companies interconnect with private producers at reasonable costs and that they buy the privately generated electricity at the same price (per kilowatt) that they would have to pay if they generated those kilowatts with their more costly fuel (Section 210 of PURPA 1978).

If the power is not going to be sold to a utility company, but instead is going to replace it, the economic feasibility can be judged in terms of savings. Most American utility companies are now charging their customers about $0.08 per KWH and this is expected to increase by 10% annually.

Sooner or later the money saved by not using the utility's power will match the facility's initial investment. It is only a matter of time before a break-even point is reached.

CHAPTER VIII

ENVIRONMENTAL IMPACTS - WATER RIGHTS

Environmental disturbances that occur with the construction of a micro-hydro plant will be nominal unless it is necessary to build a small dam. In this case, it is possible to build a fish ladder. This man-made stairway permits fish to swim upstream past the dam.

Generally, when planning on diverting or simply using a stream, it is best to check with the local soil conservation service office on the environmental division for applicable regulations (Alward 1979).

There are many laws governing rivers and streams. Some, for example, apply to refurbishing of old dams. Others deal with whether water rights are transferable when land is sold.

In regard to the ownership of the American waterways, check with the nearest water utility board or county office. They should know whether the U.S. Army Corps of Engineers or any other group has legal jurisdiction over a particular stream or river (Terry 1980).

CHAPTER IX

PRELIMINARY DESIGN

This micro-hydro plant will use the water of Richland Creek that belongs to the Tennessee River Basin.

Step One: Establish the domestic power requirements. According to Table 15 and selecting the electric appliance that the house contains, it is possible to calculate the power demand.

TABLE 15

HOUSE APPLIANCE LOAD

Appliance	KWH/month	
	Winter	Summer
Refrigerator (standard)	60	
TV (color)	42	
Blender	2	
Heater	87.4	
Coffee Maker	11	
Iron	13	
4 Lights (100 watt)	36	
Radio	10	
Sewing Machine	1	
Toaster	5	
Washing Machine	8	
Water Heater	392	
Vacuum Cleaner	8	
Clothes Dryer	87	
2 Fans		16
TOTAL	762.4	691

Average Consumption: Summer = 1 KW
Winter (with the heater) = 1.1 KW

Peak Load: (4500+700+360+350)W = 5,910 W = 6 KW
W.H. WM Ref TV

Step Two: Determine design flow and available head. From the U.S.G.S., it is possible to find the duration of daily flow at stream-gaging site of the Richland Creek. See Table 16. According to this data, it is possible to calculate the range of flow values that we are going to deal with. It is advisable to work with the flow that presents the 30 percent of the time (Q_{30}) and the flow 90% of the time (Q_{90}).

$$Q_{30} = 13.2 \text{ mi}^2 \times 2.22 \text{ ft}^3/\text{sec}/\text{mi}^2 = 29.30 \text{ ft}^3/\text{sec}$$

$$Q_{90} = 13.2 \text{ mi}^2 \times .69 \text{ ft}^3/\text{sec}/\text{mi}^2 = 9.108 \text{ ft}^3/\text{sec}$$

For smaller streams, the Q_{90} can be equal to 2.5 ft^3/sec, especially for dry seasons. In this case, it is necessary to deal with the percentage of flow required to leave running in the basin for environmental requirements.

Step Three: Head measurement. The vertical angle method was used and Table 17 shows the calculations.

Example of calculation:

$$4\phi = 3^{o}\ 27' = 3.45^{o}$$

$$\sin 3.45 = 0.0602$$

$$X_1 = d \times \sin \phi = 54.3 \times 0.0602$$

$$X_1 = 3.27 \text{ feet}$$

TABLE 16

DURATION OF DAILY FLOW

Index Number	Gaging Site	Drainage Area (mi^2)	Average Discharge (cps/mi^2)	Flow in $ft^3/sec/mi^2$ which was equal to or exceeded for indicated percent of time								
				0.5	2	10	30	50	70	80	90	98...
332	Richland Creek below Hyatt Creek at Hazelwood	13.2	2.19	...	8.30	3.90	2.22	1.53	1.07	.89	.69	.56

TABLE 17

CALCULATIONS OF VERTICAL ANGLE METHOD

Rod Station	#	Vertical <	d(ft)	x(ft)
rock at bottom	1	-3° 27'	54.3	3.27
rock	2	1° 02'	99.4	1.79
rock	2	4° 48'	75.6	6.33
big rock	3	5° 3'	73.8	6.48
small rock	3	0° 20'	71.0	-0.41
sand	4	6° 15'	78.0	8.49
rock	4	6° 18'	90.0	9.87

Gross head = 35.82 feet

Total horizontal distance = 105 feet

Net head calculation: Using the formula to calculate head loss per foot: C for PVC = 150,

$$\text{Head Loss per foot} = \left[\frac{V_e}{(1.381)(C)(R^{.63})}\right]^{1.852}$$

the following table is obtained (Table 18).

TABLE 18

HEAD LOSS

Pipe Inch	Q ft^3/sec	Area ft^2	V_e	R	$R^{.63}$	loss/foot	distance ft	total vertical loss
6	9.11	0.2	45.54	0.127	0.273	0.73	105	76.7
8	9.11	0.349	26.10	0.167	0.323	0.19	105	20
10	9.11	0.833	10.93	0.318	0.486	0.018	105	1.89

According to these results, the pipe with = 8" offer small total head loss and is cheaper than the pipe ϕ = 10".

Net head = 35.82 - 20 = 15.82 feet

Step Four: Power output calculation. The power generation can be calculated as follows:

$$KW = \frac{QH}{20} = \frac{9.11 \times 15.82 \times 0.6}{11.8} = 7.33 \text{ KW}$$

Step Five: Equipment. Based on the low head and possible flow changes, the Banki-Mitchell or cross flow turbine is the best selection. In this case, the turbine will include the frame, connecting piping, draft tube, gearing, automatic mechanical governor, fly wheel, three phase generator and switchboard.

A screen will be attached over the entrance at the penstock and a gate valve will be placed immediately above the runner. A penstock 8" PVC diameter will be extended for 105 feet.

Step Six: Cost analysis. Approximate material costs for the proposed system are given below:

Turbine and generator	\$4,000
8" gate valve	344
105' of 8" PVC pipe	252
1 ft^2 screen mesh	5
45 degree elbow (in penstock length)	15
and, if needed, 50' insulated A.W.G. #4 or #6 copper	25
	\$4,641

The present value analysis makes the following assumptions:

1. Annual expenses are 5% of the initial investment and increased 8% per year.

2. Energy savings also increased 8% per year.

3. Discount rate in cost of money averaged 13%.

Project life is 15 years with zero residual value. The calculations are presented below in Table 19.

TABLE 19

PROJECT LIFE CALCULATIONS

Year	Investment	Annual Expenses	Cash Earnings	Cash Flow	PV
0	4641			4641	(4641)
1		232	2568	2336	2067
2		251	2773	2522	1975
3		271	2995	2724	1888
4		293	3235	2949	1809
5		317	3494	3177	1724
6		302	3774	3432	1648
7		370	4076	3706	1575
8		400	4402	4002	1505
9		432	4754	4322	1439
10		467	5134	4667	1375
11		505	5445	4940	1288
12		546	5881	5335	1231
13		590	6352	5762	1176
14		637	6860	6223	1124
15		688	7409	6721	1075

Net Present Value = $18,092

Cash earnings = 7.33 KW x 8,760 hrs/yr x $0.04/kwh

Conclusions

If the assumptions and price estimates are accurate, the owner of this micro facility would add over $18,092 to his net worth over the next 15 year period by setting up this project. These results indicate that the site is feasible and should be developed.

CHAPTER X

CONCLUSIONS

From a historical standpoint, micro-hydropower has passed from a flourishing energy source to an almost abandoned state with the advent of large, sophisticated hydropower plants in the first half of the 20th century. Today, though, its widespread use is on the upswing as it is being re-introduced as an alternative means for supplying individual energy needs.

Nations like China and France are leading the way in the practical implementation of micro-hydropower while other countries like the United States are starting to experiment with pilot facilities to show its effectiveness and feasibility.

Hopefully, developing nations will begin to place more emphasis on research, education, and technology in the area of alternate energy sources. In doing this, they can at least partially free themselves from foreign dependence and they can give their people the opportunity to learn how to tap the electric potential of the streams running through their lands.

Because the costs of a micro-hydro plant are generally beyond the reach of underprivileged people who are living without electricity, it remains the responsibility of governments to subsidize small-scale hydroelectric projects if they wish to upgrade the living standards of their rural citizens or if they simply wish to slow down the migration of these people to the cities.

From a technical standpoint, more flow duration data on small streams is very much needed. The information must be recorded for at least one year on a daily basis. Since micro turbines such as the Pelton and Cross flow are designed to handle different flow rates, it is important to obtain the full range of flow variations. This will ensure that the equipment is not inefficiently oversized and unnecessarily high priced.

More research must be done in the area of micro turbine technology. A recent survey, taken by this researcher, of American turbine manufacturing companies showed none with the willingness to produce turbines capable of generating less than 10 KW.

Much of this research will be performed by universities, independent engineers, and concerned laymen. Though literature in this field has been limited, there is now a world-wide organization whose purpose it is to share information on small and micro-hydropower. Its headquarters is in Boone, North Carolina at the Department of Earth **Studies** at the Appalachian State University. With organizations such as this, it should not be too long before we reap the great benefits that lie ahead in the field of micro-hydropower technology.

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